PB87-188892

Effective Mixing Processes for SOx, Sorbent, and Coal Combustion Products

Energy and Environmental Research Corp.
Irvine, CA

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

May 87

U.S. Department of Commerce
National Technical Information Service
NTIS

EPA/600/7-87/013
May 1987

EFFECTIVE MIXING PROCESSES FOR SO_x, SORBENT, AND COAL COMBUSTION PRODUCTS

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EPA Contract 68-02-4205

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OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completin

1. REPORT NO. EPA/600/7-87/013
2.
3. R PB87-188892

4. TITLE AND SUBTITLE
Effective Mixing Processes for SO_x, Sorbent, and Coal Combustion Products

5. REPORT DATE
May 1987

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
B. M. Cetegen, T. R. Johnson, R. Payne, D. K. Moyeda, M. S. Sheldon, W. Li, and G. S. Kindt

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Energy and Environmental Research Corporation
18 Mason
Irvine, California 92718-4190

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-02-4205

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development
Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED
Final; 10/84 - 7/86

14. SPONSORING AGENCY CODE
EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is Nicholas Kresovich, Mail Drop 63, 919/541-2973.

16. ABSTRACT The report describes an evaluation of the mixing of jets of calcium based sorbents injected into large wall-fired coal burning utility boiler furnaces for sulfur dioxide (SO2) emission control. Isothermal flow experiments evaluated the mixing characteristics of single and multiple jets into idealized cross-flow streams and into flow fields simulating the upper regions of boiler furnaces, where gas temperatures are most conducive to sulfur capture. Pilot scale combustion experiments at 1.41 and 24 MW thermal input tested the dependence of overall sulfur removal efficiency on injection parameters and sorbent type. Several computational and empirical models of jet behavior were adapted for use in sorbent injection system design. An effective injection system design methodology is based on a hierarchy of design and interpretation procedures. The methodology includes: (1) use of simple empirical jet relationships to provide preliminary estimates for injection system parameters (number, size, and velocity of jets); (2) isothermal physical flow modeling of the boiler to evaluate and optimize injection system mixing parameters; and (3) coupling of jet mixing results with experimental sorbent sulfation data, or sulfation calculations, to predict the impact of mixing on overall SO2 capture.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Calcium	Pollution Control	13B	
Mixing	Utilities	Stationary Sources	13H, 07A	
Sulfur Oxides	Boilers	Utility Boilers	07B	13A
Sorbents	Sulfation			07C
Coal	Jet Mixing Flow		21D	20D
Combustion Products	Jets		21B	
Mathematical Models	Injection		12A	14G

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES
416

22. PRICE
PC#36.95/mF6.50

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ABSTRACT

This report describes a study conducted to evaluate the mixing of jets of calcium based sorbents, injected into large wall-fired coal burning utility boiler furnaces for SO_2 emission control.

Isothermal flow experiments were conducted to evaluate the mixing characteristics of single and multiple jets into idealized cross-flow streams, and into flow fields simulating the flow of combustion products in the upper regions of boiler furnaces. Injection locations of primary interest were in the vicinity of the nose arch and pendant superheaters, where in general gas temperatures are most conducive to the sulfur capture process. Subsequently, pilot scale combustion experiments at 1.41 MW and 24 MW thermal input were designed and conducted, to test the dependence of overall sulfur removal efficiency on injection parameters and sorbent type. Several computational and empirical models of jet behavior were adapted, based upon results from the experimental studies, for use in sorbent injection system design.

As a result of this study an injection system design methodology has been recommended which is based on a hierarchy of design and interpretation procedures. Specific steps include: (i) the use of simple empirical jet relationships to provide preliminary estimates for injection system parameters (number, size and velocity of jets); (ii) isothermal physical flow modeling of the boiler to evaluate and optimize injection system mixing parameters; and (iii) coupling of jet mixing results with experimental sorbent sulfation data, or sulfation calculations, to predict the impact of mixing an overall SO_2 capture.

This work was carried out by Energy and Environmental Research Corporation under contract 68-02-4205 from the U.S. Environmental Protection Agency.

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TABLE OF SYMBOLS

Symbol	Description
a,b	empirical constants
A	area, constant in eqn (3-6)
b	jet width in Section 4.0
c	concentration
C_p	specific heat at constant pressure
d	jet diameter
D	denotes substantial derivative
$\mathcal{D}$	mass diffusivity
E	model depth in Section 4.0
Fr	Froude number, gr_0/U_0^2
g	gravitational constant
G	nondimensional momentum flux in the jet, eqn (4-9)
h	enthalpy
H	superheater entrance height
i	index
I	light density
j	index
J	jet to cross flow momentum flux ratio, $\rho_0 V_0^2/\rho_\infty V_\infty^2$
k	thermal conductivity, extinction coefficient
K	extinction cross section, eqn (3-14)
L	duct depth at injection elevation in Sections 3.0 and 5.0
m,n	empirical constants
m	mass
$\dot{m}$	specific mass flux
$\dot{M}$	total mass flux
$\mathcal{M}$	molecular weight
M	nondimensional mass flux in the jet, eqn (4-9)
$\mathcal{P}$	perimenter
P	pressure
q	heat flux
Q	nondimensional temperature in the jet, eqn (4-9)

TABLE OF SYMBOLS (Continued)

Symbol	Description
r	jet radius
R	universal gas constant
Re	Reynolds number, $\rho Vd/\mu$
s	streamwise coordinate
S	jet spacing
Sc	Schmidt number, $\nu/\mathcal{D}$
t	time
T	temperature
u,U,V	velocity
V	voltage
w	mass fraction
x	cartesian coordinate (free stream direction)
X	nondimensional cartesian coordinate, x/r_0
y	cartesian coordinate (cross-flow direction)
Y	nondimensional cartesian coordinate, y/r_0
z	cartesian coordinate
Z	tracer fraction leaving furnace, eqn (6-11)

Greek Symbol	Description
α,β	entrainment constants in eqn (4-1)
γ	constant in eqn (6-11)
Δ	change
∂	partial derivative
θ	angle of jet inclination
μ	dynamic viscosity
ν	kinematic viscosity
ξ	nondimensional streamwise coordinate, s/r_0
π	3.14159
ρ	density

TABLE OF SYMBOLS (Continued)

Symbol	Description
σ	particle density in eqn (3-7)
Σ	summation
τ	time constant in eqn (3-6)
ϕ	entrainment enhancement factor, eqn (7-2)
χ	solids mass fraction, eqn (3-3)
ψ	nondimensional stream function for dfn, see eqns (4-24), (4-25)

Subscripts	Description
air	air stream
carr	carrier
D_H	hydraulic diameter
fg	flue gas
g	gas
i	ith stream
j	jet
L	loss
n	normal
o	conditions at jet origin
p	particle
sorb	sorbent
t	tangential, turbulent
T	total
wm	well-mixed
x	component in x-direction
y	component in y-direction
z	component in z-direction
∞	free stream

ABBREVIATIONS

Abbreviation	
^oC	Temperature, degrees Celsius
^oF	Temperature, degrees Fahrenheit
MW_{th}	Megawatts, thermal 1 MW = 10^6 W
MW_e	Megawatts electric
Btu	British thermal unit, 1 Btu = 1055 W-sec
lb_m	pound mass
Kg	kilogram mass 2.2 lb_m = 1 kg
μm	micrometer, 10^{-6} meter

1.0 INTRODUCTION

Injection of calcium-based sorbents into combustion chambers as a means of absorbing sulfur species generated during combustion of high sulfur fuels has gained considerable attention with the increasing concern over acid rain deposition (1). It has been estimated that the coal-burning electric utility boilers contribute about 75 percent of the SO_2 emissions and about 20 percent of the NO_x emissions which are released to the atmosphere in the United States. The use of high sulfur coals in the eastern part of the United States (especially Ohio River Valley) may be linked to the high acidity of precipitation in the northeastern United States and Canada. Therefore, the reduction of the SO_2 emissions from combustion systems utilizing high sulfur coals has been identified as one approach to alleviating the acid rain problem. Among several options, dry desulfurization of furnace gases containing SO_2 has been studied for the past twenty years because of its retrofit application potential and economic feasibility.

Dry desulfurization process basically involves two steps. These are:

- The thermal decomposition of calcium compounds (sorbents) such as $CaCO_3$ and $Ca(OH)_2$ upon heating. The decomposition can be represented by the reactions,

$$\begin{array}{lcl} CaCO_3 \text{ (limestone)} & & CaO + CO_2 \\ & + \text{ heat} \longrightarrow & \\ Ca(OH)_2 \text{ (lime)} & & CaO + H_2O \end{array}$$

- The second step involves sulfation on the surfaces of porous CaO particles with SO_2 in the furnace gas stream. This heterogeneous chemical reaction can be written as a one-step reaction,

$$CaO \text{ (solid)} + SO_2 \text{ (gas)} + 1/2\ O_2 \text{ (gas)} \longrightarrow CaSO_4 \text{ (solid)}$$

Recent work in this technology has better defined conditions for optimization of sulfur removal efficiency. Experimental evidence suggests that sorbents lose their reactivity when they are injected into the high temperature regions of a combustor. Experiments in a large number of bench and pilot scale combustors (2,3) have identified an optimum temperature range for sorbent injection between 1200°C (2192°F) and 1250°C (2282°F) for typical calcium sorbents such as $CaCO_3$ and $Ca(OH)_2$. Modeling studies of the sulfation process indicate that sorbents need to have residence times of the order of one second in a sulfation temperature window ($800°C < T < 1200°C$, $1472°F < T < 2192°F$) for effective sorbent utilization. The limits of this temperature window are dictated by sorbent reactivity as well as equilibrium and kinetic constraints. Injection of sorbents into large combustion chambers therefore requires that materials should be injected into the combustor remote from the flames to avoid high temperatures and sorbent deactivation; i.e., near the beginning of the sulfation temperature window.

The location of the favorable temperature zone in boilers is in the upper furnace, usually beginning near the exit of the radiant furnace and extending into the convective passes (4). A practical means of sorbent injection into boiler combustion chambers at these locations is by sorbent-laden jets using air as the carrier medium. This is achieved by injection of sorbent jets into the cross-flow stream of combustion products. The primary objectives of the study undertaken by Energy and Environmental Research Corporation (EER) for the U.S. Environmental Protection Agency (EPA) under Contract EPA 68-02-4205 were, firstly, to identify the key features of the jet injection process for the particular systems (i.e., wall-fired boiler upper furnace configurations); and, secondly, to study the influence of jet injection aerodynamics on sulfur capture. In particular, the jet injection schemes which provide rapid mixing of the sorbent stream near the beginning of the favorable temperature zone were investigated to develop a sorbent injection system design methodology for use in full scale boiler injection scheme designs.

The study of sorbent jet injection into boiler upper furnaces is complicated by the complex flow field and thermal environment prevailing in this part of the boiler. It is believed that a successful injection system design should provide adequate coverage of the furnace flow with sorbent within a small space and in a short time.

This final report is a documentation of studies conducted to formulate an effective sorbent injection system design methodology for wall-fired boilers. First, studies of upper furnace flow field and thermal environment were conducted to identify the general characteristics of the systems considered. The results of this study are summarized in Section 2.0 of this report. Second, a comprehensive literature search was conducted and isothermal modeling studies were performed to understand the mixing and dispersion of sorbent injection jets into the boiler flow field. The results are reported in Sections 3.0 and 4.0 of this report. Third, the findings from these studies were evaluated in combustion experiments at two different scales (1.24 MW_{th} and 24 MW_{th}). The effects of sorbent jet injection parameters on the sulfur capture for several sorbents ($Ca(OH)_2$, $CaCO_3$) were studied in these experiments. The results are reported in Sections 5.0 and 6,0 of this report. Fourth, a sorbent injection system design methodology was developed based on these studies. Section 7.0 summarizes the developed sorbent injection system design methodology for the wall-fired boiler. Although it was developed for wall-fired boilers, it is believed that the elements of the methodology are equally applicable for the tangentially-fired boilers considered for upper furnace sorbent injection. Examples of the methodology application are given in Section 8.0 for the wall-fired Edgewater boiler which is EPA's LIMB demonstration site. The conclusions from this study are summarized in Section 9.0. Section 10 includes the references.

2.0 UPPER FURNACE SORBENT INJECTION FOR SO_2 CONTROL

The application of the dry desulfurization process is intended mainly as a retrofit technology for utility boilers burning fuels with medium to high sulfur content. In order to achieve optimum process efficiency, certain process requirements must be satisfied within the constraints and operational characteristics of existing combustors. Two key process requirements are:

- a limitation on maximum temperatures to which sorbent particles can be exposed. For most sorbents, this temperature is about 1200°C (2192°F).
- a residence time requirement of approximately one second in the sulfation temperature window ($800 < T < 1200$°C) for effective sulfation of sorbent particles.

The first of these requirements dictates the location where sorbents should be injected into the combustor. The second concerns the most efficient use of the available residence time in a boiler by optimizing the sorbent injection system and mixing of the sorbent with the furnace flow. Therefore, the two elements, the thermal environment and flow field in boiler furnaces need to be studied to identify the injection location and mixing constraints. In the following subsections, the general characteristics of boiler thermal environment are first discussed to determine the location of the sorbent injection zone. Having identified the injection zone, the furnace flow characteristics in this zone and downstream, are explored for optimization of sorbent mixing with furnace gases and utilization of the available residence time.

2.1 Thermal Environment

Thermal constraints of the desulfurization process require studying the thermal environment in boilers. Generalization of thermal characteristics of all boilers cannot be achieved readily, because of large variations in operational characteristics, fuel properties, slagging and fouling conditions, etc. For the purposes of determining the optimum sorbent injection location, it is, however, necessary to know the bulk gas temperature distribution through the upper furnace and superheater/reheater region where the 1200°C isotherm lies. A characteristic temperature which provides an indication of furnace temperature levels is the radiant furnace exit temperature. The radiant furnace exit temperature can be defined to be the average bulk flue gas temperature at a horizontal plane at the nose level as shown in Figure 2-1. There are several ways of determining the radiant furnace exit temperature:

- Measurements
- Empirical Furnace Efficiency Formulae and Heat Balances
- Heat Transfer Modeling

Although measurements and model predictions are available for some boilers, these individual cases do not readily allow a generalization of exit temperatures. Measurements are generally difficult and expensive for large utility boilers. The furnace exit temperatures determined from empirical furnace efficiency formulae, on the other hand, are not sufficiently accurate for the purposes of identifying the sorbent injection location. Another option for thermal analysis is heat transfer modeling.

Two and three dimensional heat transfer models have recently been effectively utilized to predict temperature and heat flux distributions in utility boiler furnaces. Comparisons of model predictions with field measurements indicate (5) that good agreement between measured and predicted gas temperature distributions can be obtained if the model input parameters are accurately prescribed.

Measured furnace exit temperatures for eight boilers are listed in Table 2-1. These temperatures are shown in Figure 2-2 as a function of the heat release rate per unit cooled surface area. Furnace exit temperatures generally increase with higher heat loadings, although a certain amount of scatter is evident, reflecting differences in boiler design and operation. Temperatures range from 1200°C (2192°F) to 1400°C (2552°F). Thus, the

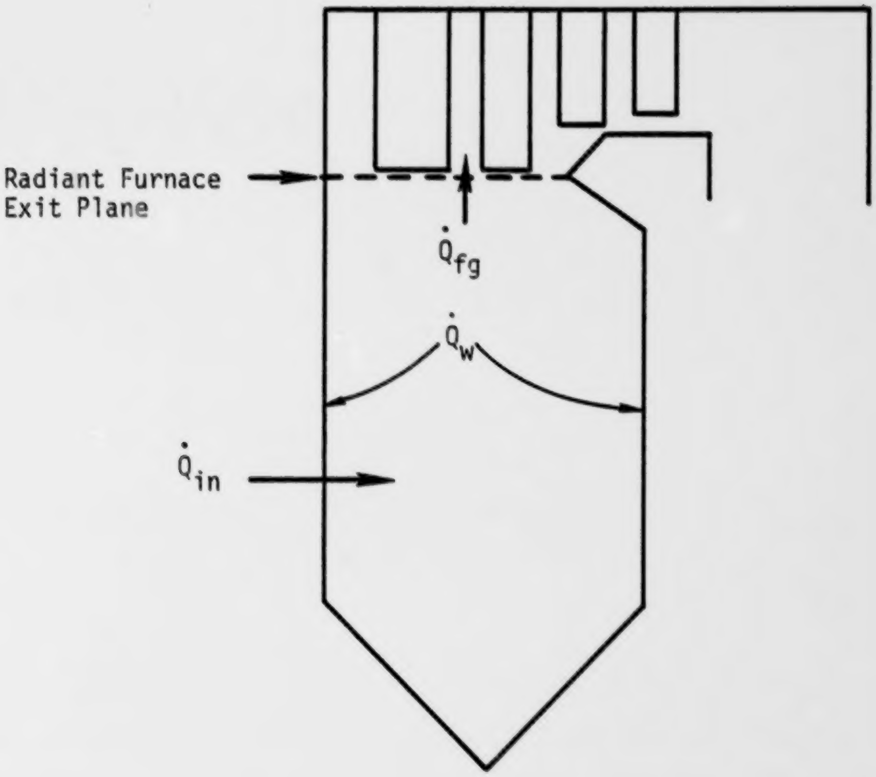

Radiant Furnace Exit Plane
$\dot{Q}_{fg}$
$\dot{Q}_w$
$\dot{Q}_{in}$

Figure 2-1. Furnace schematic and boiler heat balance.

TABLE 2-1. BOILER CHARACTERISTICS AND THERMAL PARAMETERS

Boiler	Firing Configuration	Upper Furnace Configuration (See Fig.2-3)	Coal		Thermal Load MW	SR_T	Heat Release Parameters					T_{fg}*	
			AFR_{st}	HV MJ/kg			FD MW/m^3	BZFD MW/m^3	CSA m^2	HR/CSA MW/m^2	HR/PA MW/m^2	°C	°F
Weiner III (division wall)	Opposed-Wall	Tower	9.4	30.0	2000	1.30	0.11	0.32	5901	0.34	4.84	1100	2030
Shawnee (division wall)	Front-Wall	A	9.0	25.0	433	1.20	0.25	0.48	1148	0.38	4.22	1260	2300
Labadie 4	T-Fired	D	9.0	28.0	1483	1.31	0.21	0.37	2492	0.60	5.82	1315	2400
Mill Creek 1	T-Fired	D	9.0	27.5	793	1.26	0.20	0.47	1733	0.46	5.0	1230	2246
Duck Creek	Front-Wall	C	9.4	28.0	1260	1.20	0.18	0.41	1868	0.67	6.5	1385	2525
Conesville	T-Fired	D	9.1	25.0	1220	1.20	0.19	0.56	2171	0.56	5.73	1425	2600
Homer City	Opposed Wall	B	10.8	29.5	2000	1.30	0.19	0.474	2894	0.61	5.78	1413	2575
Hoot Lake	T-Fired	D	6.04	16.3	130	1.20	0.21	0.764	605	0.22	3.50	--	--
WIPCO	Front-Wall	A	9.0	28.2	80	1.24	0.211	0.607	287	0.28	2.55	1121	2049

AFR_{st}: Stoichiometric air fuel mass ratio, kg air/kg coal

HV: Heating Value

SR_T: Total Stoichiometric Ratio, $AFR/(AFR)_{st}$

FD: Firing density, MW/m^3

BZFD: Burner zone firing density, MW/m^3

CSA: Cooled surface area, m^2

HR/CSA: Heat release/cooled surface area, MW/m^2

HR/PA: Heat release/plan area, MW/m^2

* Temperature in the horizontal plane at the nose elevation

(estimated from in-plant measurements)

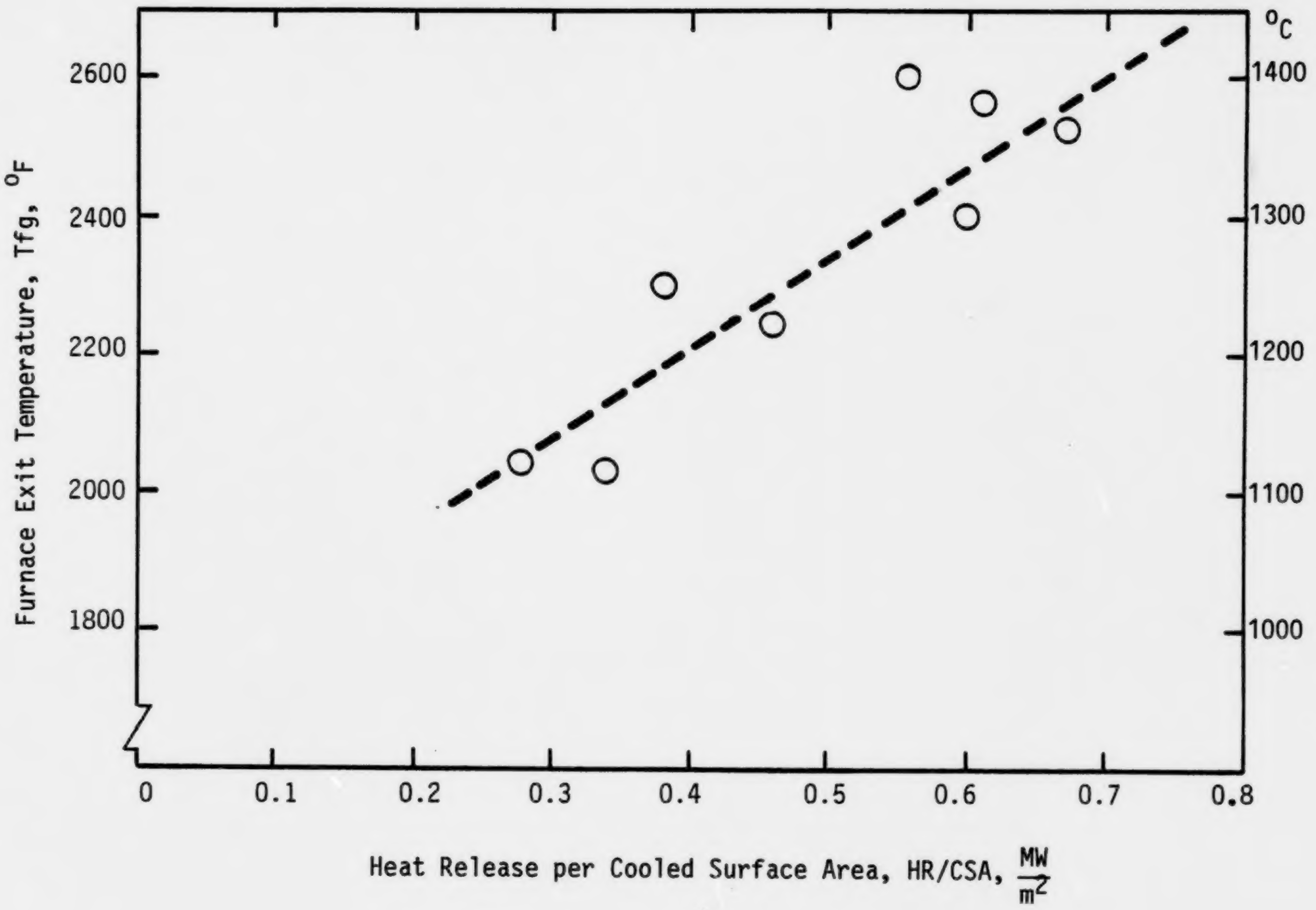


Figure 2-2. Measured furnace exit temperatures.

beginning of the sulfation window for highly loaded boilers is at least above the radiant furnace exit plane.

Based on the characteristics of these different types of boiler, as well as experience with many other boilers, the most likely location for sorbent injection lies in the upper furnace in the vicinity of the radiant furnace exit plane.

2.2 Furnace Flow Field

Identification of the approximate sorbent injection location allows examination of the flow field in this region of the boilers where sorbent is to be mixed with the furnace flow. The general characteristics of the flow field are primarily determined by the geometry of the furnace enclosure. Therefore, it is of interest to study typical upper furnace geometries and to identify their common features.

2.2.1 Upper Furnace Geometries

Figure 2-3 shows the upper furnace designs of wall-fired and tangentially fired boilers of different sizes and manufacturers, operating in the U.S., compiled from various sources (6,7). Table 2-2 summarizes these furnace configurations with respect to firing configuration, boiler manufacturer and unit size. Configurations A, B, and C are the three most distinct upper furnace designs. Others (D and E) are similar to configuration B. Configuration A is typical of small 50-200 MW_e units which could be generally either wall or tangentially fired. Configuration B is employed by both Foster-Wheeler and Babcock and Wilcox for large front-wall fired boilers. This configuration is similar to configuration D which is typical of Combustion Engineering's tangentially fired boiler design. Configuration C is unique in the construction of the transition from radiant furnace to the back pass. This configuration was used in some of the wall-fired boiler designs of Riley Stoker Corporation.

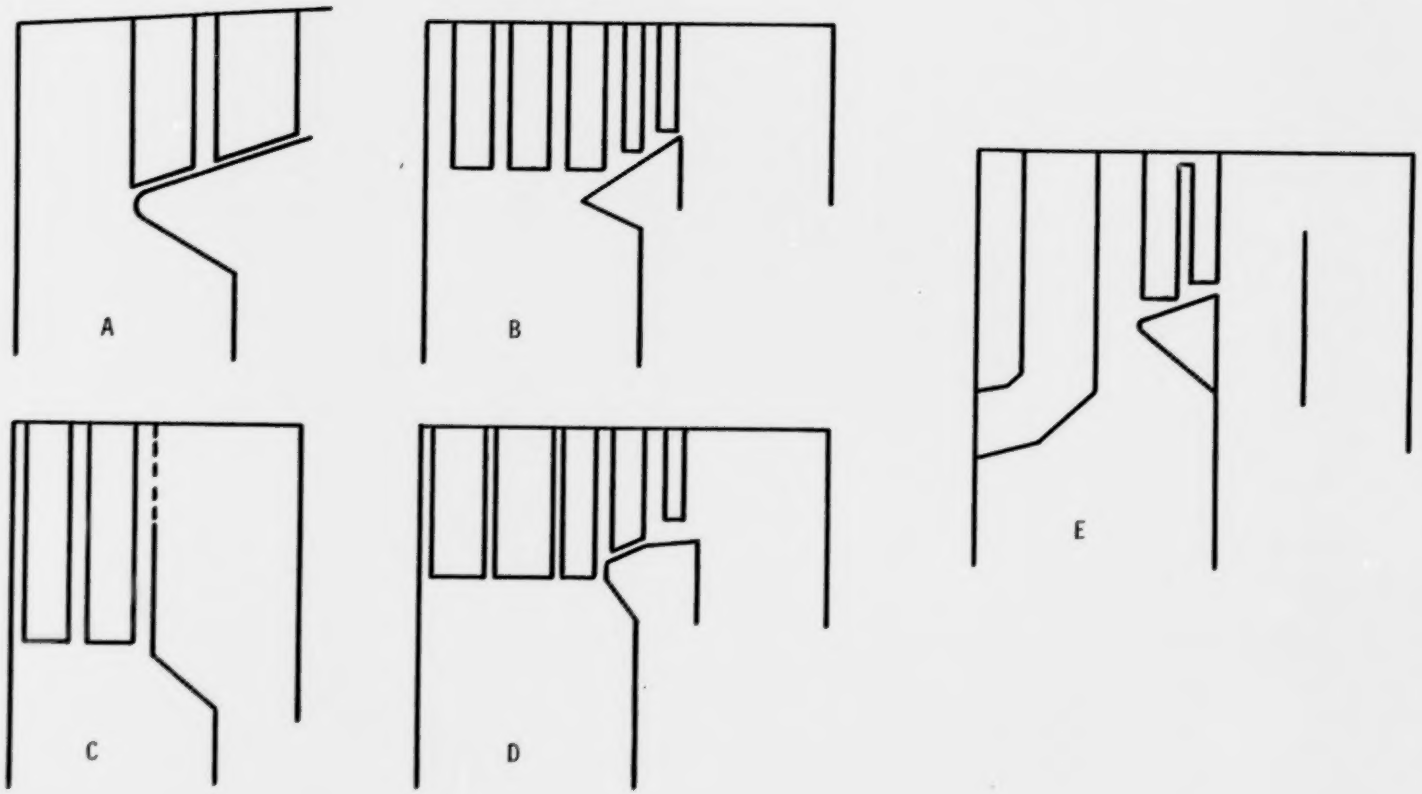


Figure 2-3. Upper furnace configurations.

TABLE 2-2. BOILER UPPER FURNACE CONFIGURATIONS

Configuration	Firing Conf.	Boiler Manufacturer	Unit Size, MW_e
A	Wall-Fired	Foster-Wheeler	50-200
	Wall-Fired	Babcock & Wilcox	50-500
	T-Fired	Combustion Engineering	50-200
	Wall-Fired	Riley-Stoker	50-200
B	Wall-Fired	Foster-Wheeler	500-800
	Wall-Fired	Babcock & Wilcox	500-800
C	Wall-Fired	Riley-Stoker	200-500
D	T-Fired	Combustion Engineering	200-800
E	Wall-Fired Divided Back Pass	Foster-Wheeler	500-800

2.2.2 Upper Furnace Flow Field

A knowledge of the upper furnace flow field is important in the design of sorbent injection systems since it provides key input for the study of injection aerodynamics. The common features of the upper furnace flow field are determined by the furnace geometry. These are:

- acceleration of the flow leaving the furnace due to the contraction (nose).
- change in the direction of the flow as it enters the superheater banks.
- presence of pendant superheater banks which channel the flow and prevent sideways mixing of flue gas.

Figure 2-4 shows the upper furnace flow patterns for the boiler designs identified in Figure 2-3. One other common characteristic of the flow field is the recirculation zone at the corner between the roof and front wall. In all configurations, the flow accelerates around the nose and in many cases, flow separates above the nose. At the nose elevation, the distribution of the flue gas mass flow is generally such that a large portion of the furnace flow is confined near the nose. One feature of upper furnace Configuration C that is different from others, is the presence of a large recirculation zone behind the screen tubes where the flow makes a sharp turn. This kind of information on the upper furnace flow field is valuable in the general consideration of various injection options.

2.3 Temperature History in Upper Furnace

The thermal environment (gas temperature distributions) and the flow field (velocity or mass flow distributions) together define the temperature history of the pockets of flue gas and particles as they travel in the combustion chamber. The temperature history is one of the important parameters in the dry desulfurization process since the temperature-time

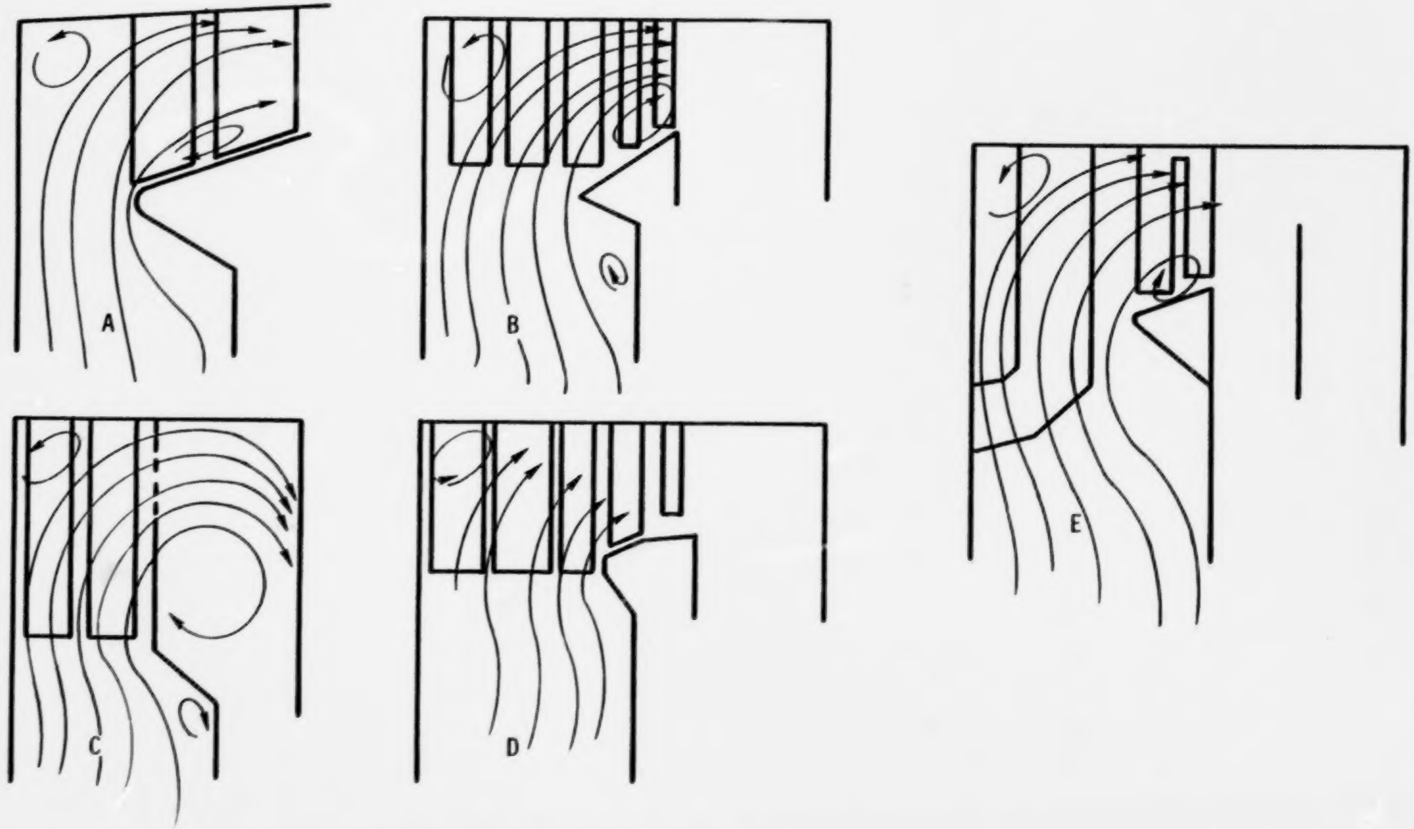


Figure 2-4. Upper furnace flow fields.

relationship experienced by the sorbent particles can have an impact on the process efficiency. Globally, a residence time of about one second in the temperature zone between 1200°C (2192°F) and 800°C (1472°F) is required for effective sulfation of sorbent particles. A study of temperature histories for several U.S. boilers showed that the time scales were of the order of one second, as shown in Figure 2-5. It is apparent that the rate at which the flue gas temperature falls in the boiler (the gas quench rate) can be significantly different for boilers with different design and operating characteristics. Because of the limited residence time in the sulfation temperature window ($800 < T < 1200^{\circ}C$), it becomes important to mix the sorbent stream with the flue gas rapidly so that sulfation reactions could progress effectively. Hence, the sorbent injection characteristics, determining how rapidly the sorbent stream is mixed with the combustion products, becomes key in implementing the process to the U.S. boilers.

2.4 Practical Means of Injection

The main function of the sorbent injection system is to disperse small sorbent particles into the furnace gas stream as uniformly as possible. This should be achieved in a small space downstream of the injection location to utilize all the available residence time in the sulfation window. As discussed in the previous subsection, the residence times in the sulfation temperature window for U.S. boilers are short and therefore they should be most effectively utilized.

Several methods of injecting particles into large furnace cross sections can be envisioned. These are:

- ballistic injection of particles
- slurry injection of sorbents
- sorbent particle laden jet injection

The first method is not practical and would require a medium in which particles can be accelerated to very high velocities to achieve penetration into the furnace flow. For example, a 10 μm sorbent particle would have to

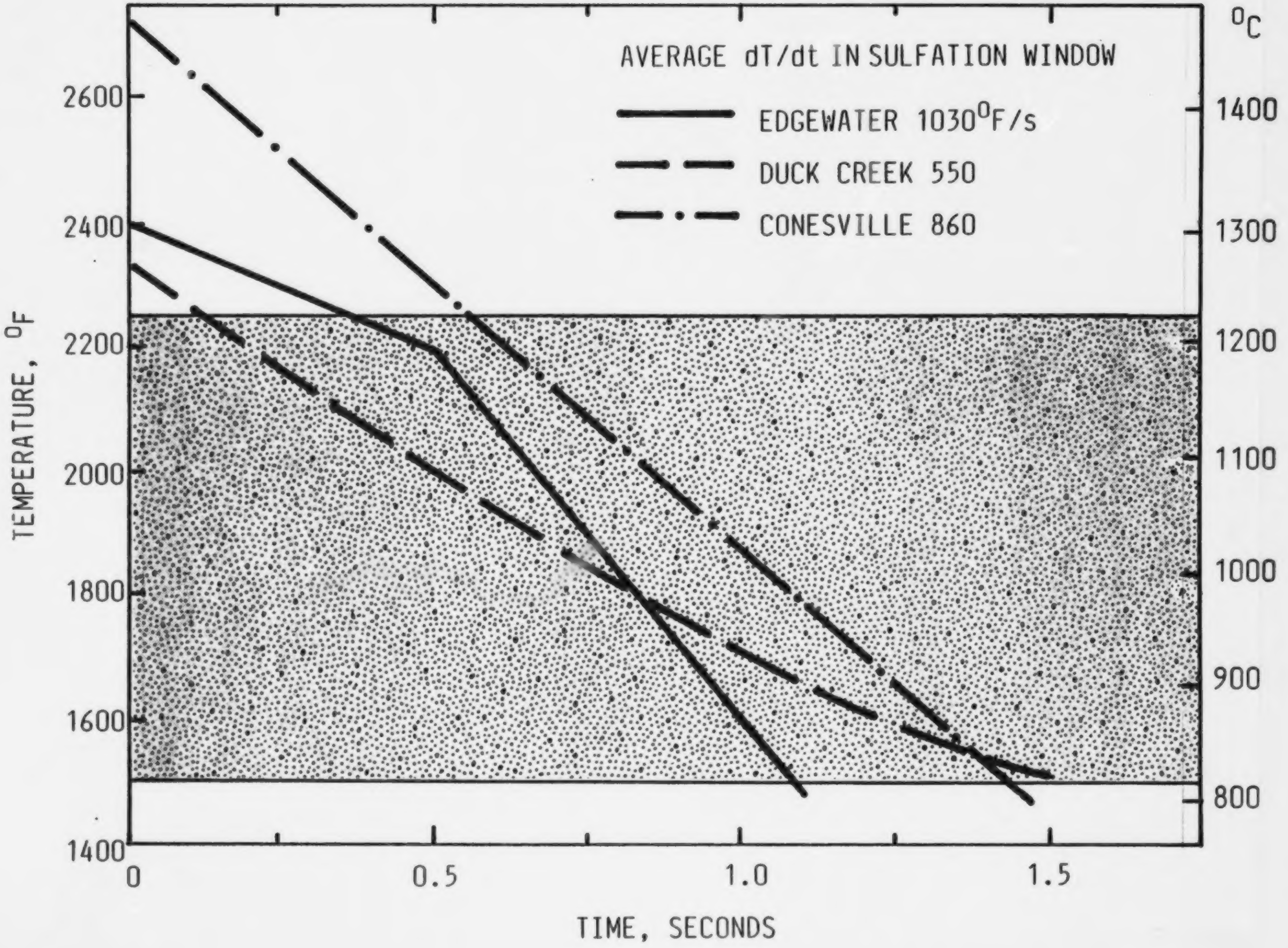


Figure 2-5. Temperature-time (or quench rate) profiles for several U.S. boilers.

be injected at a velocity of 9×10^2 m/s to penetrate 0.3 meter into quiescent air at 1200°C. Hence, ballistic injection is impractical and use of a carrier medium such as liquid or gas is required for carrying sorbent particles.

Slurry injection is a viable means for sorbent injection and it has a number of advantages and disadvantages compared to solid-gas injection. Injection of sorbent particles in a water slurry requires some mechanism of dispersing the slurry stream into the furnace flow. This can be achieved by using pressure jet or air blast atomizers. One advantage of this scheme is that the sorbent may be protected from high temperatures during the drying or evaporation period in the spray. Because of the poor penetration characteristics of an evaporating spray, spray nozzles would have to be arranged in the furnace cross section to provide good coverage of the flow or augmented with gas jets. The first, however, necessitates equipment exposed to the hostile environment of the boiler furnace and major operational problems such as pluggage, erosion, and slagging of nozzles can be experienced. In addition, the evaporation of the water would have some impact on the furnace thermal efficiency. The second method would have the features of an initially droplet-laden gas jet which would be similar to particle laden gas jet injection discussed below.

Sorbent injection by means of particle-laden jets has several advantages. Firstly, sorbent jet nozzles can be located on the furnace walls without any equipment in the furnace flow stream. Secondly, sorbent penetration, dispersion and mixing can be controlled by the jet injection parameters.

In this project, sorbent injection by means of particle-laden gas jets placed on the furnace walls has been investigated. The main objective of this project was to establish an upper furnace sorbent injection system design methodology for full scale design of sorbent injection systems for wall-fired boilers. In particular, the essential elements required in the development of such a methodology are:

- to identify the key jet injection parameters influencing penetration and mixing characteristics of sorbent jets issuing into the cross stream of hot combustion products

- to determine the impact of these parameters on mixing and dispersion of sorbent into the furnace flow

- to investigate the impact of those parameters affecting the mixing conditions on sulfur capture for typical sorbents

In order to achieve the first goal, an extensive review of available literature on jet injection was carried out. This was followed by a series of isothermal model tests to determine the influence of the key jet injection parameters on jet penetration (trajectories) and mixing in the particular geometries and flow fields of boiler upper furnaces. In the course of these investigations, it was found that information on the entrainment of jets in cross flow, a very important element of the mixing process, was scarce. This prompted development of a simple entrainment model of a jet-in-cross flow which was calibrated with experiments to give realistic estimates of mixing rates especially in the near field of injection jets. The use of this model enabled to identify some key features of the jet injection process which could not be studied by isothermal modeling i.e., non-isothermal effects. Based on these isothermal and computational jet modeling studies, the parameters which have the largest impacts on the mixing of sorbent streams with furnace gases were identified and tested in a pilot scale combustion experiment.

A series of sorbent injection tests were conducted with several typical sorbents ($CaCO_3$ and $Ca(OH)_2$) to study the effect of injection parameters on sulfur capture. The current state of the understanding of the sulfur capture process was utilized in conjunction with the mixing tests described earlier to explain sulfur capture results. The prediction methods used to explain the combustion tests along with the studies of jet mixing were utilized to formulate injection system design procedures of different levels of sophistication. These were:

- an empirical approach to determine the number, size and velocity of injection jets to provide good penetration and coverage of the furnace flow.

- isothermal modeling to refine the previous estimates and provide a predictive tool to determine the expected sulfur removal efficiency.

- combination of jet injection models and sulfation/calcination models to predict the sulfur removal efficiency.

This next section concerns the review of cross-flow jet injection literature and the isothermal experiments conducted to study sorbent jet injection in boiler geometries.

3.0 ISOTHERMAL MODELING STUDIES

Isothermal modeling of boiler flow field and jet injection is a valuable tool in identifying the general characteristics of the boiler upper furnace flow field and jet dispersion. The main objective of these tests was to identify the key injection parameters influencing the mixing of injection jets in the particular flow field of utility boilers. In this project, a series of isothermal flow experiments were conducted in two acrylic models to study upper furnace flow fields and jet injection in boiler configurations. Experiments included:

- flow visualization by neutrally-buoyant soap bubbles and smoke to identify flow patterns.
- velocity measurements by hot wire anemometry to determine velocity distributions.
- gas tracer measurements by methane gas injection to quantify dispersion in jets.
- particle concentration measurements by a laser-extinction technique to determine dispersion of particles in sorbent jets.

3.1 Experimental Systems

Figure 3-1 shows EER's physical flow modeling facilities. The experimental set-up used in these experiments consisted of a metered air supply system and the flow diagnostic equipment. In this study, models were operated at approximately atmospheric pressure with air as the working fluid medium. A commercial Sage action neutrally-buoyant soap bubble generator was used for flow visualization with slit lighting. Smoke was generated by a commercial Rosco Smoke Generator (PRO-3000). Velocity measurements were made with a TSI Model 1054A single hot wire anemometer and its associated electronic components.

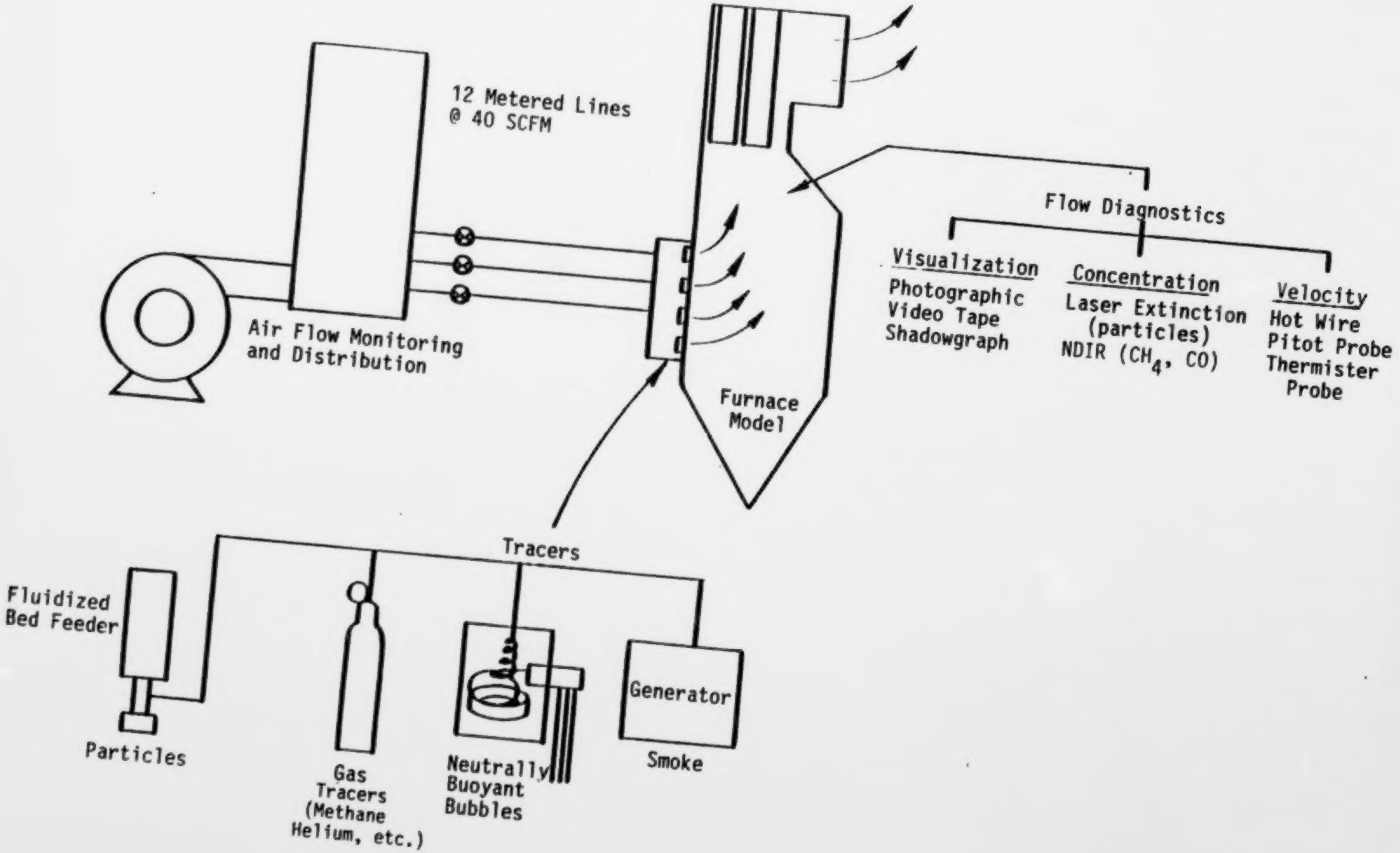

12 Metered Lines
@ 40 SCFM
Air Flow Monitoring
and Distribution
Furnace
Model
Flow Diagnostics
Visualization
Photographic
Video Tape
Shadowgraph
Concentration
Laser Extinction
(particles)
NDIR (CH_4, CO)
Velocity
Hot Wire
Pitot Probe
Thermister
Probe
Tracers
Fluidized
Bed Feeder
Particles
Gas
Tracers
(Methane
Helium, etc.)
Neutrally
Buoyant
Bubbles
Generator
Smoke

Figure 3-1. Physical flow modeling facility.

In the following, the experiments conducted in a upper furnace flow cell are discussed first. These tests involved flow field characterization and studies of jet penetration and dispersion in a slice of a upper furnace model. For the results to be more widely applicable, jet penetration tests were conducted in an alternate configuration model. The results of these tests are discussed in Subsection 3.3.

3.2 Experiments in the Upper Furnace Flow Cell

Figure 3-2 shows an isometric sketch of the upper furnace flow cell. This model was built as a representative section of a wall-fired boiler upper furnace. The model was intended for simulation of a boiler upper furnace flow field by studying the flow in a representative slice of the whole boiler width. The model width was chosen to avoid the interference of the wall boundary layers with the injection jet studies. The specific geometry was that of the EPA's wall-fired LIMB demonstration boiler (Edgewater). The model was constructed from 0.64 cm (0.25 inch) thick acrylic plates for ease of flow visualization.

Three key similarity criteria were considered in the construction of this model. These were:

- Geometric similarity which insures the similarity of the overall flow field
- Dynamic similarity of the flow field based on Reynolds number of the bulk flow.
- Pressure drop similarity through the convective tube banks which has an effect on the separation bubble formed above the nose constriction.

A 1:7 geometric scale was selected. The model width simulated 1/4 of the full scale boiler width. The model was operated at an air flow rate of 600 scfm which gave Reynolds numbers (based on the furnace hydraulic

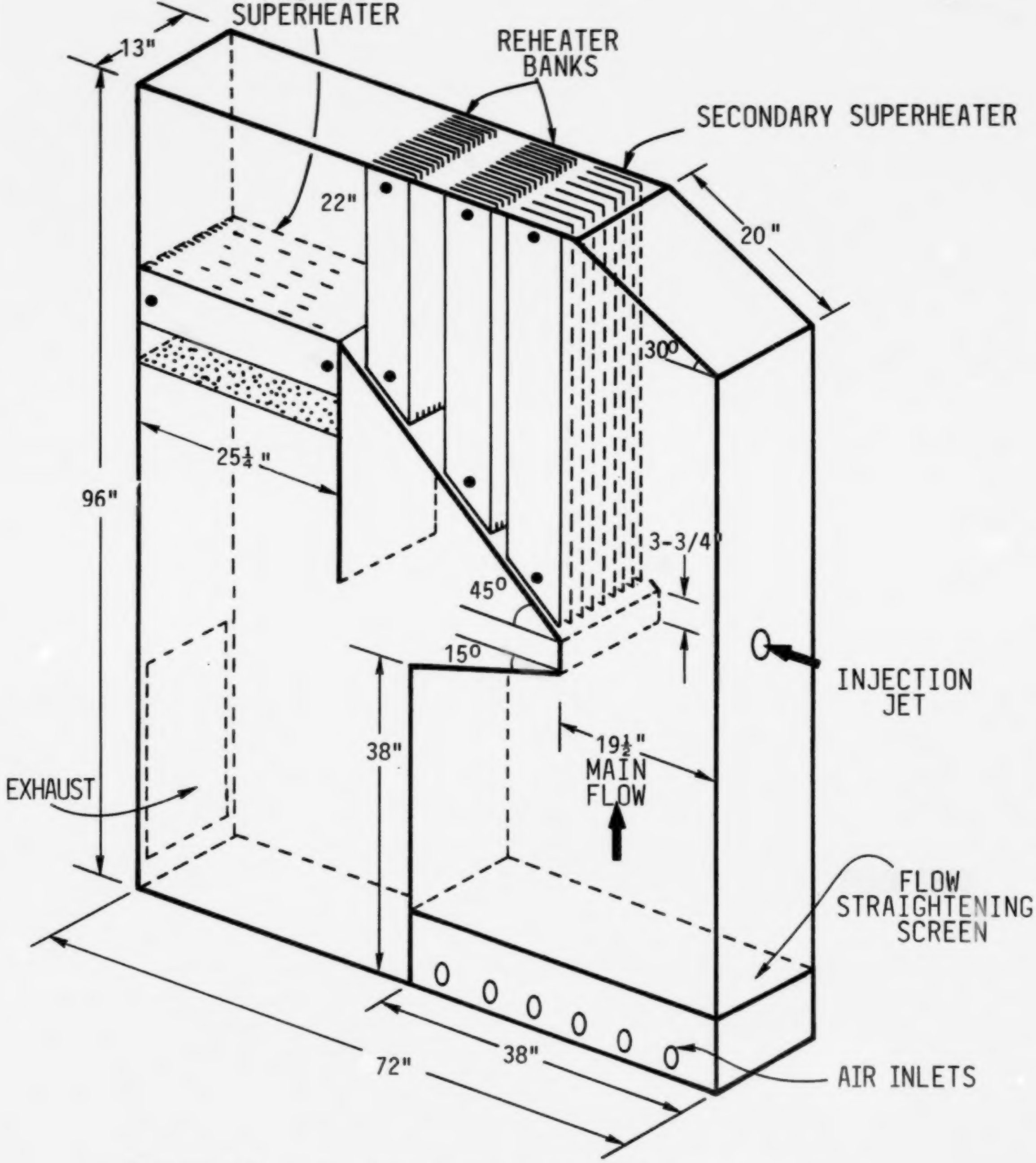

PRIMARY SUPERHEATER
REHEATER BANKS
SECONDARY SUPERHEATER
13"
22"
20"
30°
96"
25¼"
3-3/4"
45°
15°
INJECTION JET
38"
19½"
MAIN FLOW
EXHAUST
FLOW STRAIGHTENING SCREEN
38"
72"
AIR INLETS

Figure 3-2. Isometric view of upper furnace flow cell.

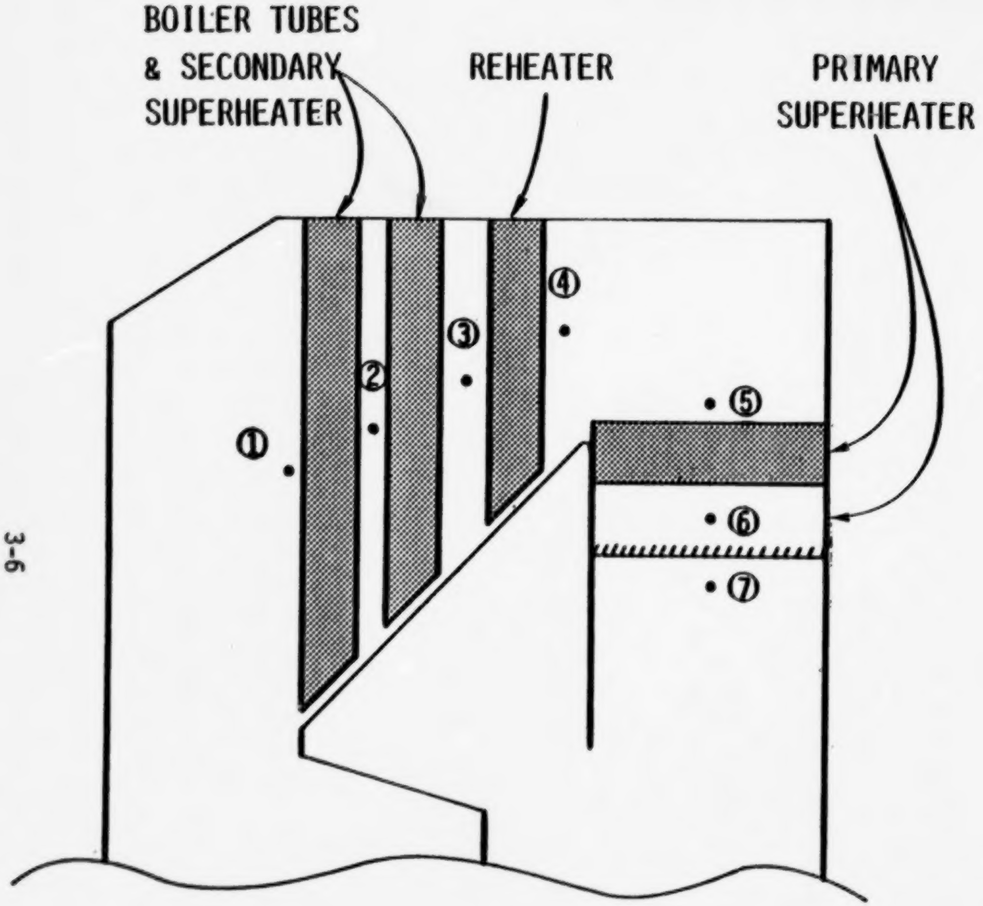
diameter) of 28,000 and 44,000 at the lower furnace cross section and the nose plane respectively. These high Reynolds numbers ensured turbulent flow and similarity of the flow patterns. The thickness of the turbulent boundary layers developing along the walls was calculated to be small compared with the model width. The pressure loss coefficients across the superheater and reheater tube banks were matched with the measured values from the full scale boiler. Figure 3-3 gives the comparison of the measured model and prototype pressure loss coefficients. The pressure loss coefficients were modeled satisfactorily.

The tests involved flow field screening, jet injection scheme screening and gas concentration measurements for selected test conditions. In the following, the results of these tests are discussed.

3.2.1 Flow Field Screening and Characterization

Flow visualization tests were first conducted to identify the general features of the upper furnace flow field. Time exposure photographs of the neutrally-buoyant soap bubble streaks were taken. Figure 3-4 shows the streaklines sketched from a time exposure photograph of the bubble-streaks. During these tests, blockage by perforated plates was provided to simulate the recirculation zone above the burner region (not simulated in the sketch shown). Several key features of the flow field were the sudden acceleration of the flow around the nose and subsequent formation of a recirculation eddy above the nose. In addition to these, the flow changed direction from vertical to horizontal.

Velocity profiles were measured at the nose and at the superheater inlet planes to quantify the flow distributions. The profiles of measured velocity at these planes are shown in Figure 3-5 and 3-6. Velocity measurements showed only small variations across the model width (i.e. in the Y direction). Hence, the measured velocities were averaged across the model width. The main feature of the measured velocity profiles at the two planes was the high velocity region near the nose and the recirculation region in


BOILER TUBES & SECONDARY SUPERHEATER
REHEATER
PRIMARY SUPERHEATER
①
②
③
④
⑤
⑥
⑦

PRESSURE LOSS COEFFICIENTS

POINTS	BOILER	MODEL
1-2	0	0
2-4	17	19
5-7	39	34

Figure 3-3. Edgewater flow cell pressure loss coefficients.

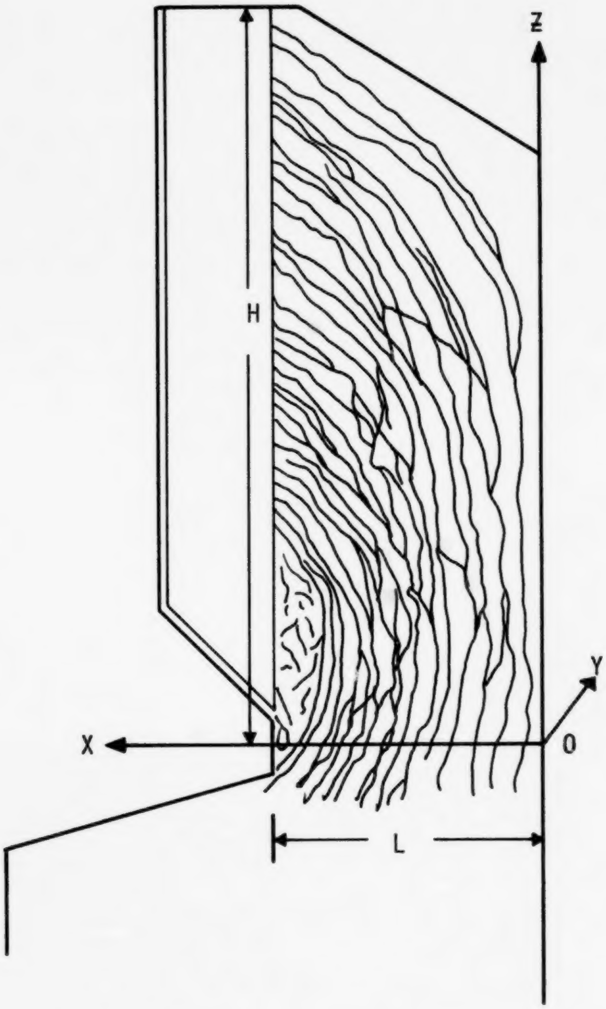


Figure 3-4. Sketch of soap bubble streaks in the upper furnace flow field.

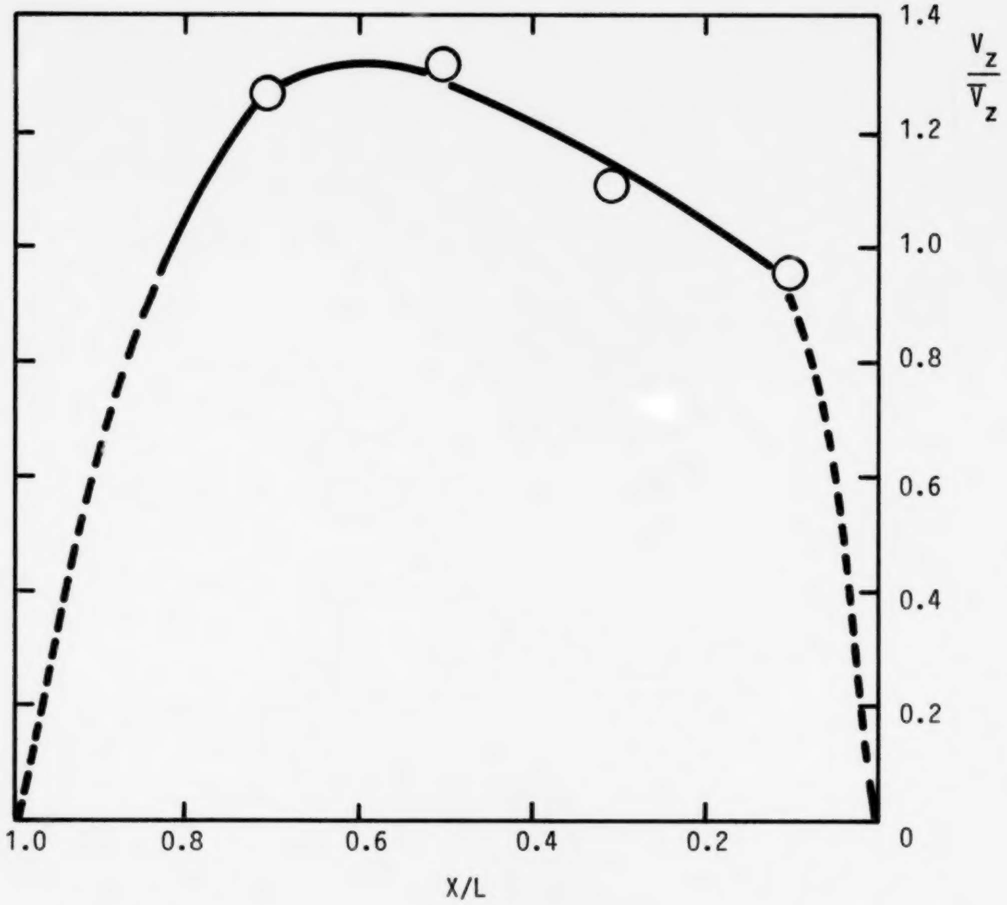


Figure 3-5. Normalized velocity profile at the nose plane (for coordinate references, see Figure 3-4).

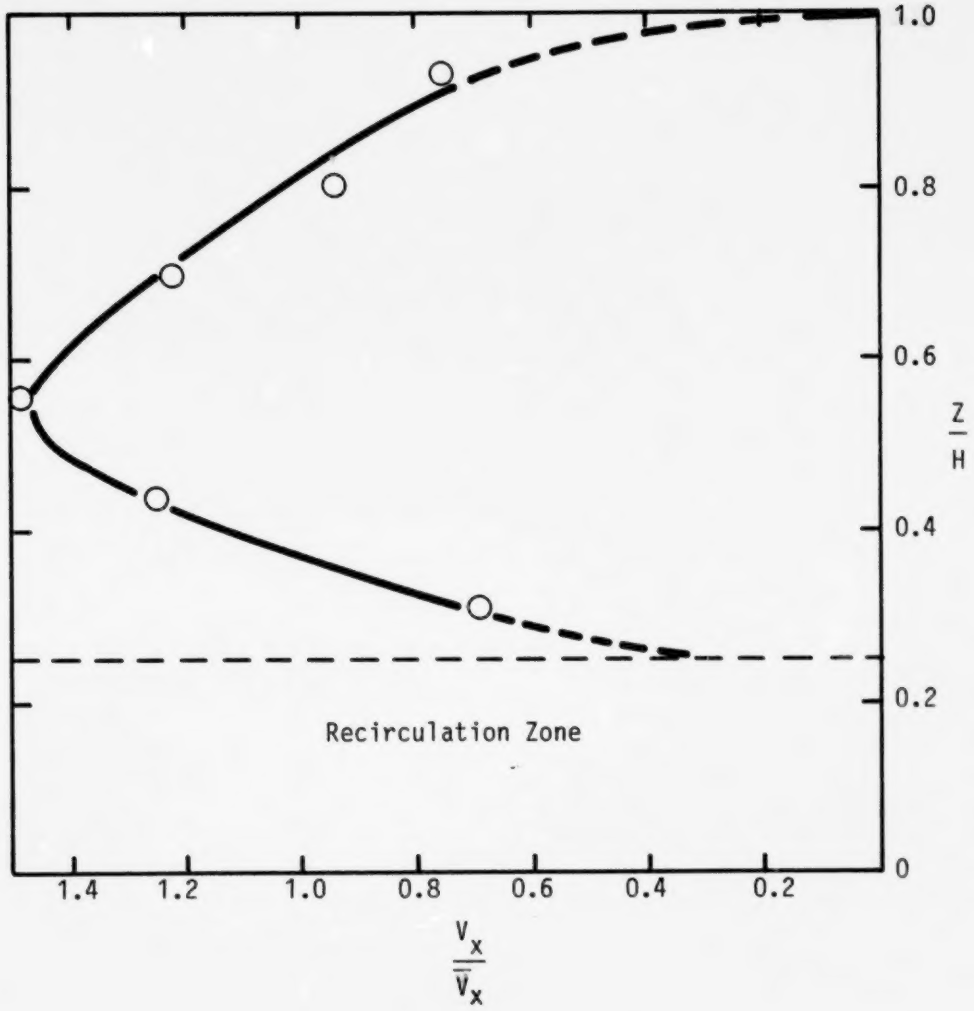


Figure 3-6. Normalized mean velocity profile at the superheater inlet plane (for coordinate references, see Figure 3-4).

the vicinity of the nose. These profiles had the same features as the velocity profiles measured in boilers.

3.2.2 Jet Injection Studies

Before starting jet injection studies, a detailed survey of the parameters influencing jet penetration and dispersion was conducted. Information on jets in cross flow from literature was compiled. Many of the studies (8,9,10,11,12,13,14) were motivated from the VSTOL aircraft studies, turbine jet dilution studies, and plume spread. In many of these studies (8,9,11,13,14), a single round jet was injected at right angles to a uniform flow field in a wind tunnel. Typically, the jets were issued from nozzles with diameters ranging from a few millimeters to several centimeters. Studies included determination of the jet trajectory and spread with some investigations (9,10) of detailed jet characterization. The objective of this review was to investigate the key parameters which determine the jet trajectory and control jet penetration. In this survey, only those studies which had the range of the parameters closest to those which might be encountered in boiler sorbent injection applications were considered. Table 3-1 gives a list of the jet trajectory studies re-evaluated. Jet trajectory correlations mostly had the form of

$$\frac{y}{d_o} = a\, J^{n} \left(\frac{x}{d_o}\right)^{m} \tag{3-1}$$

where J is the jet to cross flow momentum flux ratio defined as $\rho_o V_o{}^2/\rho_\infty V_\infty^2$. d_o is the jet nozzle diameter; x and y are the cartesian coordinates shown in Figure 3-7; a, n and m are empirical constants. In Table 3-1, the ranges of the momentum flux ratios for the correlations are also tabulated. A detailed regression analysis of the jet trajectory correlations was conducted to determine the constant a and the exponents n and m in equation (3-1). This analysis yielded,

TABLE 3-1. SUMMARY OF JET TRAJECTORY CORRELATIONS

Investigator	Trajectory Correlation	Range of J
Shandorov (25)	$\frac{y}{d_o} = J^{0.39} \left(\frac{x}{d_o}\right)^{0.39}$	2-20
Ivanov (10)	$\frac{y}{d_o} = J^{0.43} \left(\frac{x}{d_o}\right)^{0.33}$	13-1000
Patrick (26)	$\frac{y}{d_o} = J^{0.43} \left(\frac{x}{d_o}\right)^{0.38}$	40-500
Keffer & Baines (8)	$\frac{y}{d_o} = 0.85J^{0.5} \left(\frac{x}{d_o}\right)^{0.30}$	4-100
Kamotani & Greber (9)	$\frac{y}{d_o} = 0.89J^{0.47} \left(\frac{x}{d_o}\right)^{0.36}$	15-60
Pratte & Baines (11)	$\frac{y}{d_o} = 2.0J^{0.31} \left(\frac{x}{d_o}\right)^{0.38}$	25-1225
Platten and Keffer (13)	$\frac{y}{d_o} = 1.75J^{0.31} \left(\frac{x}{d_o}\right)^{0.38}$	16-64
Present Work Average	$\frac{y}{d_o} = J^{0.43} \left(\frac{x}{d_o}\right)^{0.36}$	Cover the above range

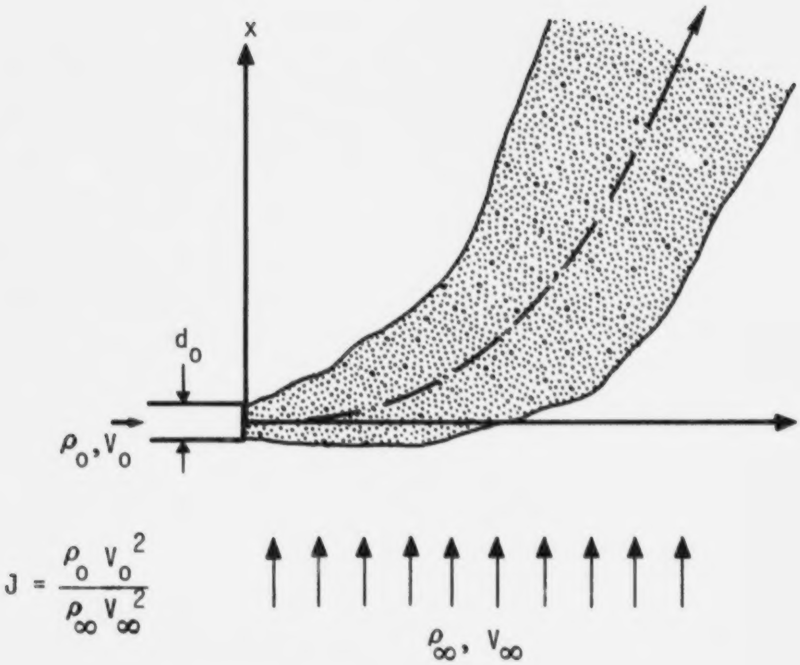

x
d_o
ρ_o, V_o
$J = \frac{\rho_o V_o^2}{\rho_\infty V_\infty^2}$
ρ_∞, V_∞

Figure 3-7. Orientation of a jet in cross flow.

$$\frac{y}{d_o} = J^{0.43}\left(\frac{x}{d_o}\right)^{0.36} \tag{3-2}$$

The comparison of the results from this correlation and the individual correlations listed in Table 3-1 is shown in Figure 3-8. The predictions from each correlation were plotted against those from equation (3-2). Therefore, the 45° line corresponds to the exact agreement of the correlations with the correlation described by equation (3-2). It is seen that the average correlation given by equation (3-2) is a good representation of the trajectory data in the literature, especially if one considers the differences in the definitions of jet centerline trajectories. Furthermore, this correlation was found to be in good agreement with the trajectory measurements from the present study which were based on the centerline of the smoke traces. Jet trajectories produced from a computational jet model, described later, were also in excellent agreement with the predictions from equation (3-2).

The form of the trajectory equations given by equation (3-1), suggests that the key parameters determining the penetration characteristics of jets are:

- the jet nozzle size (or diameter)
- jet to cross flow momentum ratio, $J = \dfrac{\rho_o V_o^2}{\rho_\infty V_\infty^2}$

A small diameter jet bends faster than a large diameter jet at the same momentum flux ratio. This also has implications in terms of the entrainment of the jets since bending occurs as a result of momentum exchange which, for the most part, takes place by entrainment. For a given jet nozzle diameter, the increase in the jet to cross flow momentum flux ratio increases the jet penetration. Hence, the momentum flux ratio can be envisioned as the stiffness of the jet.

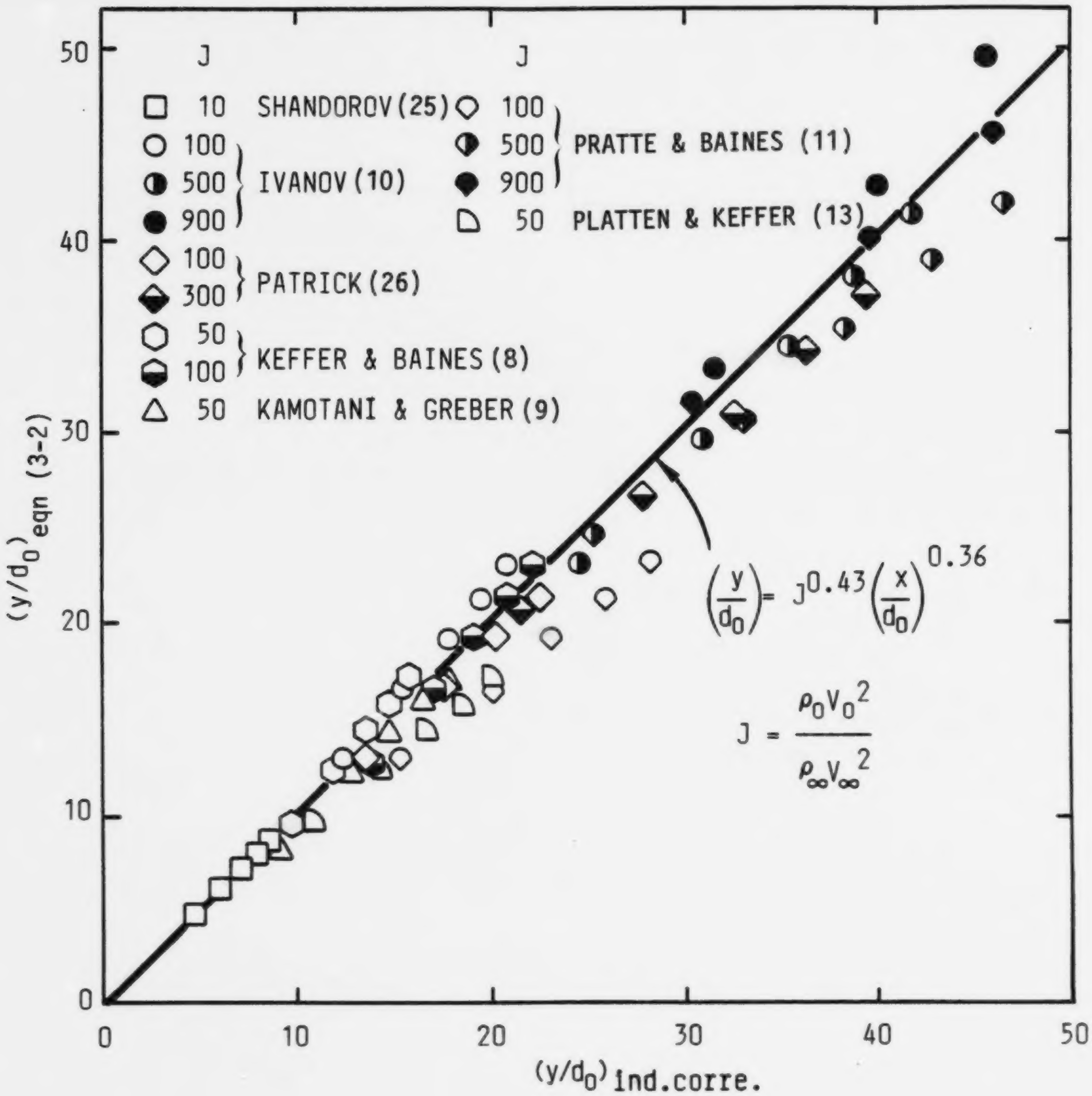


Figure 3-8. Comparison of jet trajectory correlations.

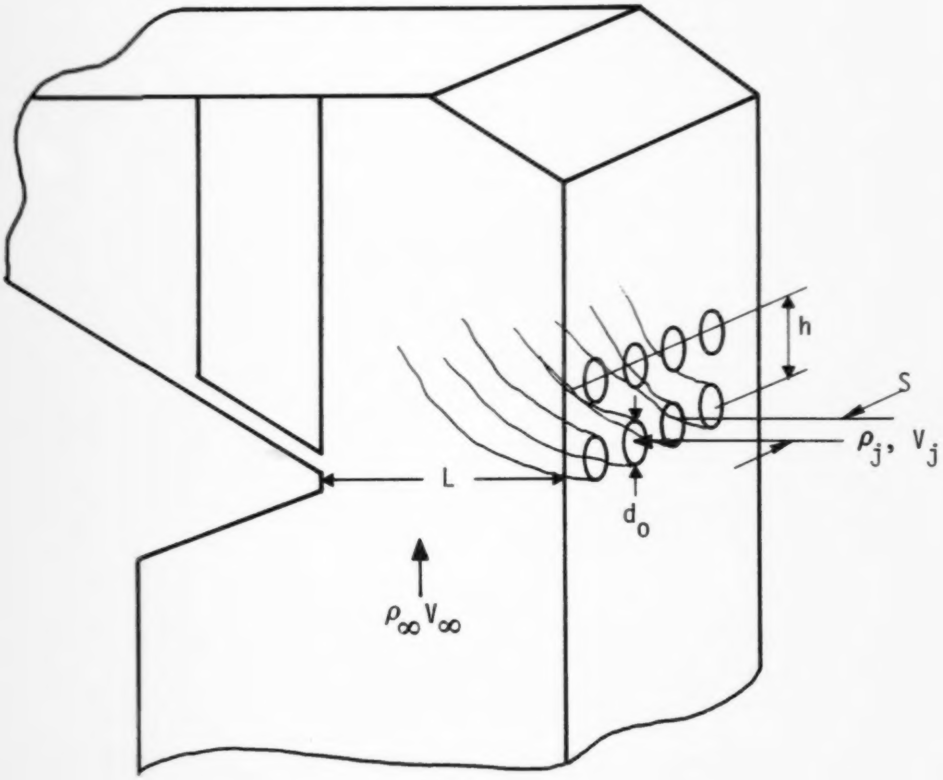
The two key parameters controlling the bending and entrainment of gas jets in cross flow are jet nozzle diameter and the momentum flux ratio. Therefore, studies of jet injection have concentrated on evaluating the effects of these parameters on the behavior of jets injected into a complex boiler upper furnace flow field. In the following the results of screening tests with smoke injection and gas tracer measurements are concurrently discussed.

3.2.3 Injection System Screening and Dispersion Tests

The jet injection studies in the flow cell were designed to evaluate the mixing and dispersion characteristics of jets in a simulated boiler flow field. First, screening studies were carried out by introducing smoke into the jet fluid. This allowed visual observations of how jets mixed and dispersed within the furnace flow. Smoke visualization was only used as a qualitative tool since there are uncertainties and difficulties with interpretation of smoke traces from time exposure photographs of smoke images. One of the difficulties in interpreting smoke images occurs in recirculating flow fields (such as the upper furnace flow field studied here) where smoke can be trapped in the recirculation zones and may lead to misinterpretation. Similarly, smoke intensity on photographic recordings represent a line of sight integral view and this again may lead to difficulties in interpretation. All these factors were taken into account when interpreting the smoke traces from the simulated sorbent jets. In spite of the difficulties and shortcomings of the smoke visualization technique, it is a widely used, helpful technique for qualitative measures. In this study, smoke visualization provided valuable qualitative information on mixing and dispersion. Selected test cases which showed good visual dispersion of the jets were studied in detail by making tracer measurements at a downstream location from the injection point into the model. This involved introducing a small amount of methane (CH_4) into the jet fluid and taking measurements of the tracer concentrations over a grid plane downstream of injection locations. This facilitated comparisons of the dispersion patterns from the smoke traces and concentration measurements. The distributions of the normalized tracer concentrations were also used later in this report to predict the sulfur capture potential for specific injection system configurations. In the following the test matrix for these tests is discussed.

3.2.3.1 Test Matrix

The objective of this study was to investigate the influence of key jet parameters on the mixing of jets with the cross flow stream. Based on the jet trajectory studies, the jet diameter and the momentum flux ratio were identified as the two key parameters. In addition to these parameters affecting jet mixing in an unconfined, uniform cross flow; a series of tests was aimed at studying the confinement effects, namely; the separation between jets in the case of a row of closely spaced jets, and the depth confinement which is related to the proximity of the opposite wall towards which the jets penetrate. The test variables are schematically explained in Figure 3-9. Among these variables, the jet momentum and confinement parameters were properly non-dimensionalized so that the number of independent variables are reduced significantly. This is common practice in fluid similitude and allows the study of key dimensionless groups instead of a large number of dimensional parameters. Diameter effects were studied for 0.84, 1.27 and 2.54 cm diameter jets. Changes in the jet diameter also allowed variation of the depth confinement parameter, L/d, without changing the chamber depth, L. Four levels of jet momentum flux ratio were investigated. In isothermal tests, the momentum flux ratio simply reduces to the square of the ratio of the jet to cross flow velocity. In all the experiments and the results shown subsequently, jet momentum flux ratio was defined based on the cross flow conditions prevailing at the nose plane. Calculations were based on the average cross-flow velocity which was obtained by dividing the volume flow rate of the main flow by the cross sectional area at the nose plane. Jet location was also one of the parameters studied in the upper furnace flow cell by changing the injection elevation of the jets injected from the front wall, and jets injected from the roof and from the back wall near the nose location. The side spacing parameter, S/d_0, was varied by increasing the number of jets with the same diameter. Table 3-2 summarizes the ranges and values of the test parameters for this study.


h
S
ρ_j, V_j
L
d_o
$\rho_\infty V_\infty$

Parameters: d_o, $\frac{\rho_j V_j^2}{\rho_\infty V_\infty^2}$, $\frac{h}{L}$, $\frac{L}{d_o}$, $\frac{S}{d_o}$

Figure 3-9. Parameters studied in the isothermal flow cell.

TABLE 3-2. JET INJECTION PARAMETERS

Jet Parameter	Value
Diameter, d_o, cm	0.84, 1.27, 2.54
Momentum Flux Ratio, J	50, 100, 150, 250
Jet Location wrt nose, $\frac{h}{L}$	-0.5, 0.0, +0.5
Confinement Parameter, $\frac{L}{d_o}$	19.5, 39.0, 59.0
Side Spacing, $\frac{S}{d_o}$	8.7, 13.0, 26.0

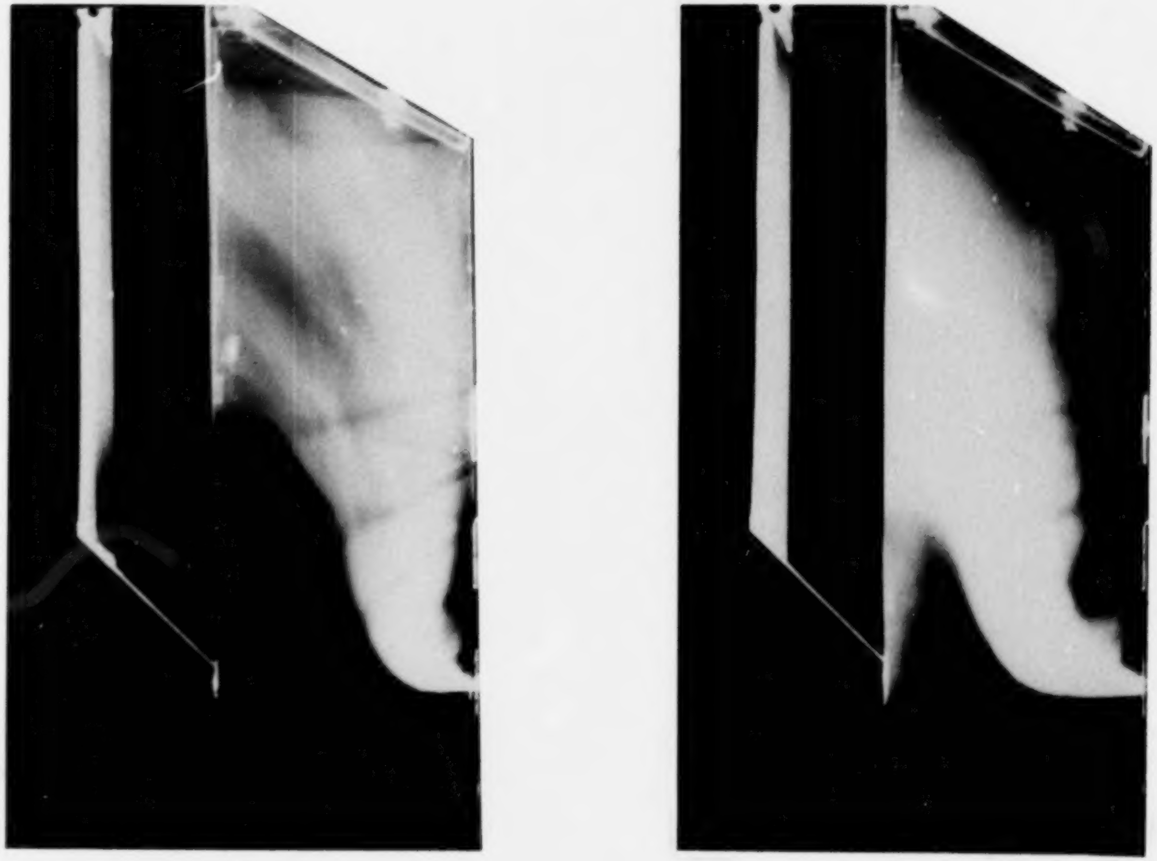
3.2.3.2 Test Results

In this section, the smoke photographs and the comparison between the smoke traces and the concentration measurements are discussed in the following order:

- Effect of jet diameter, d_0 and depth confinement, d_0
- Effect of jet momentum flux, J
- Effect of side spacing of jets, S/d_0
- Effect of jet location, h/d_0

Jet Diameter

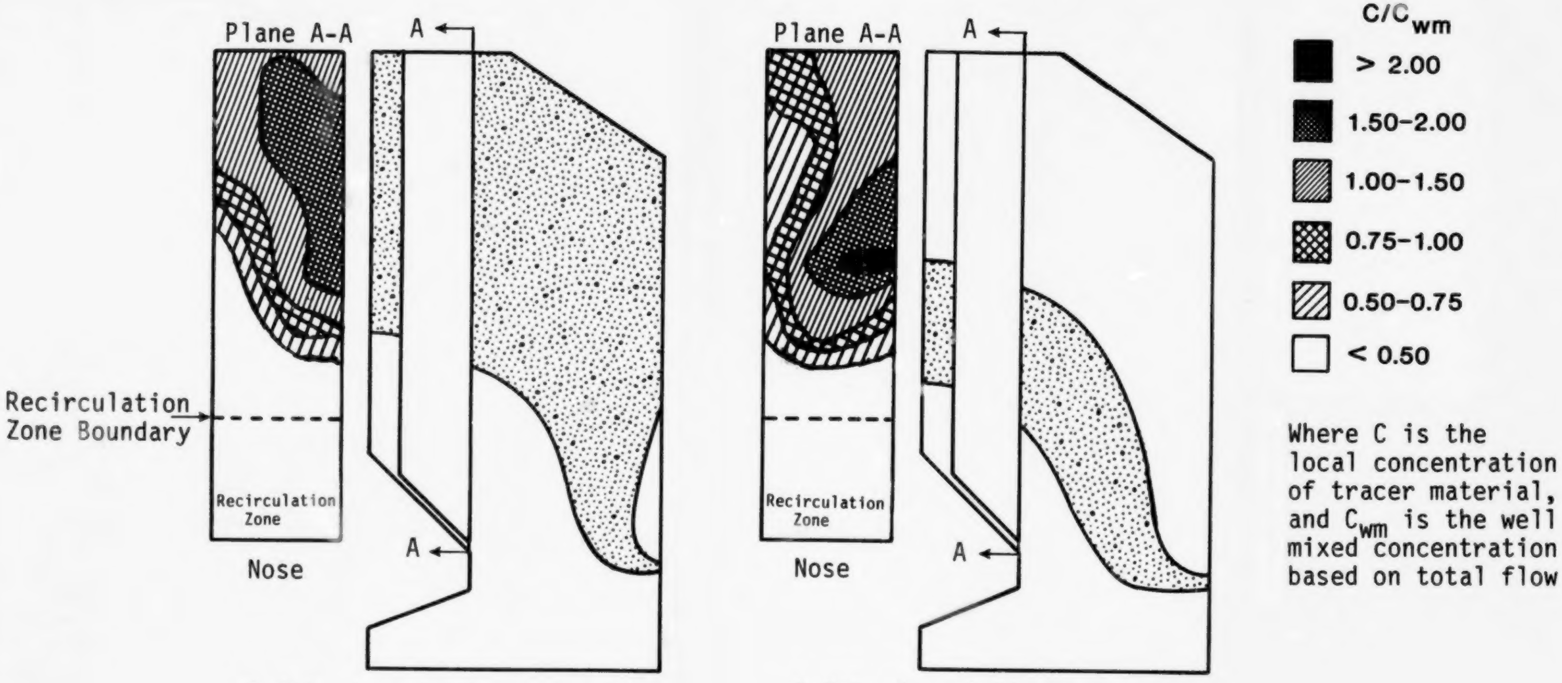
Figure 3-10 shows the smoke photographs of the 1.27 cm and 2.54 cm jets injected from the front wall at the nose elevation. It is apparent that the larger diameter jet penetrates further across the furnace depth for the same jet momentum flux ratio, J. The smaller diameter jet mixes faster with the cross flow and is carried by the cross-flow stream. Figure 3-11 compares the jet dispersion sketched from smoke photographs with the normalized tracer concentration profiles. In the concentration maps, locally measured concentrations were normalized with the well-mixed concentration at the model outlet. The well-mixed tracer concentrations measured at the exhaust always agreed well with the calculated well-mixed concentration from the flow rates of the tracer and the air. Several observations based on Figure 3-11 are worth mentioning. First, the lower boundary of the jet (leading edge) matches reasonably well with the lowest level of normalized tracer concentration, 0.5. Second, the trailing edge boundary for the 2.54 cm. diameter jet does not correspond to a distinct tracer contour. This is mainly due to the difficulty of identifying the trailing edge of the jet from the smoke trace which is strongly dependent on the smoke intensity and the concentration of the smoke introduced into the jet. However, it is expected that the cross flow peels the jet fluid from the jet, creating a wake with varying concentrations of the tracer. Therefore, the profile of the trailing edge of the jet is open to misinterpretation, although the leading edge is clearly marked with the smoke. In the concentration maps, there is also some



d_o = 1.27 cm.

d_o = 2.54 cm.

Figure 3-10. Photographs of 1.27 cm. and 2.54 cm. jets at a momentum flux ratio of 100.


Plane A-A
A
A
Recirculation Zone Boundary
Recirculation Zone
Nose
Plane A-A
A
A
Recirculation Zone
Nose
C/C_{wm}
■ > 2.00
▩ 1.50–2.00
▨ 1.00–1.50
▦ 0.75–1.00
▧ 0.50–0.75
□ < 0.50
Where C is the local concentration of tracer material, and C_{wm} is the well mixed concentration based on total flow

1 Jet, d_o = 1.27 cm, J = 100

1 Jet, d_o = 2.54 cm, J = 100

Figure 3-11. Comparison of smoke traces and concentration profiles for a single jet at J = 100. Effect of jet diameter.

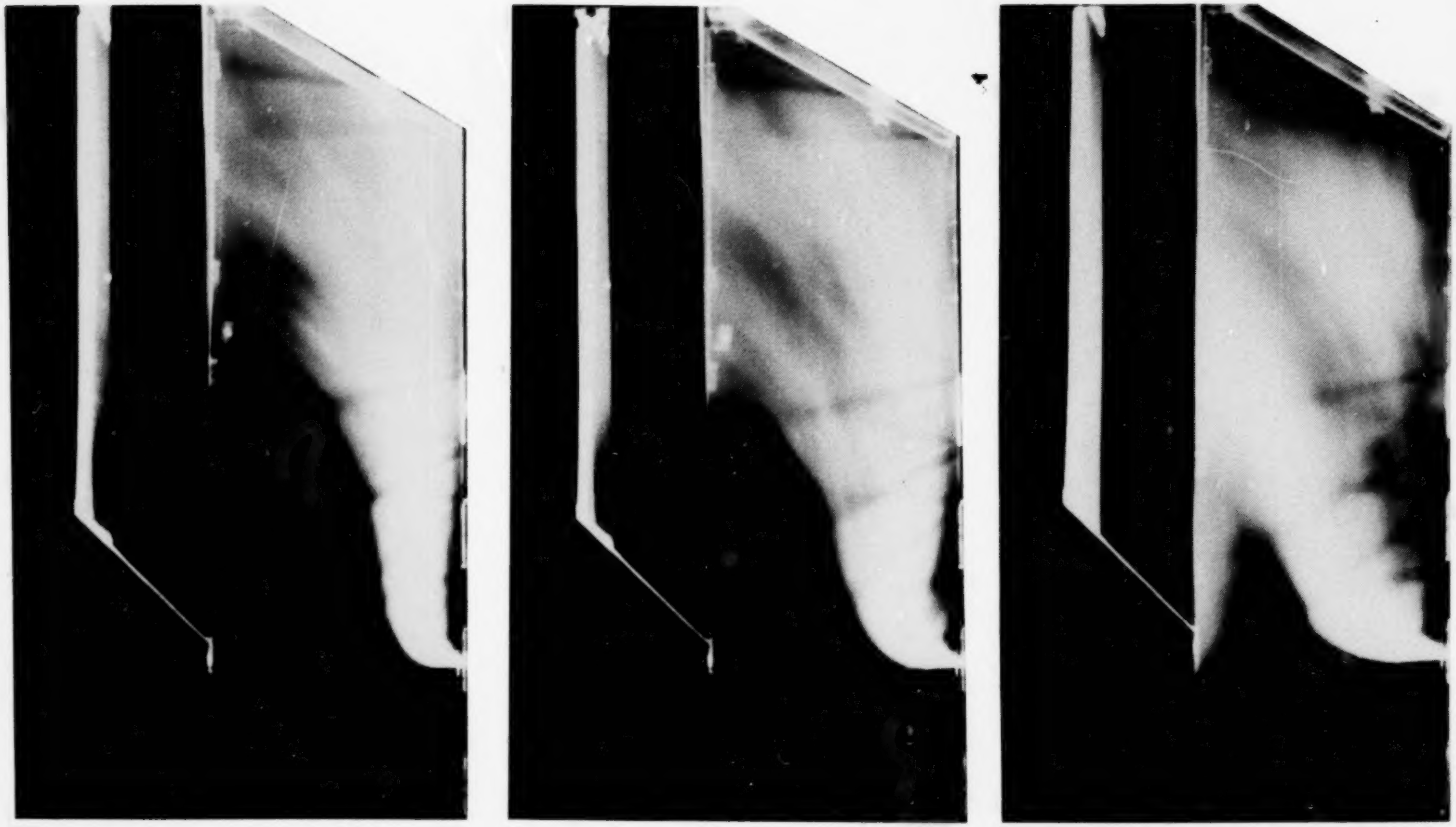
side-to-side asymmetry which is believed to be due to the distortion of the jet caused by the main flow.

Figure 3-11 also shows that the distribution of tracer (or sorbent in the actual case) can be altered by changing the penetration of the injection jet. In this case, this is achieved by changing the jet diameter.

Jet Momentum

Figure 3-12 shows photographs of a 1.27 cm diameter jet injected from the front wall at the nose level at three momentum flux ratios. It can be seen that as the jet momentum increases, the penetration of the jet into the furnace increases and its location as it enters the superheater plates changes. The comparison with tracer measurements, depicted in Figure 3-13, reveals the same observations, namely: the leading edge boundaries of the jets agree reasonably well with the smoke traces. However, the trailing edge of the jet marked by the smoke underestimates the jet fluid spread. Similar observations were noted for a 2.54 cm diameter jet injected at three momentum flux ratios shown in Figures 3-14 and 3-15. It is apparent that the 2.54 cm diameter jet penetrates farther into the cross flow than the 1.27 cm diameter jet at the same momentum flux ratio (see Figures 3-12 and 3-14). In Figure 3-15, for $J = 150$, some of the jet fluid is trapped in the recirculation zone just above the nose (see Figure 3-4).

Based on these observations, it is clear that the penetration and spread of the jets can be altered by changing either the diameter or jet to cross flow momentum flux ratio, or both simultaneously. This provides a means of controlling the mixing of the jet stream with the furnace flow. The tracer fluid (or sorbent) distribution can be tailored such that the sorbent is distributed as uniformly as possible with respect to the furnace mass flow, to provide optimum mixing conditions for the sulfur capture process.



1 Jet, d_o = 1.27 cm, J = 50

1 Jet, d_o = 1.27 cm, J = 100

1 Jet, d_o = 1.27 cm, J = 150

Figure 3-12. Photographs of a 1.27 cm diameter jet at three momentum flux ratios.

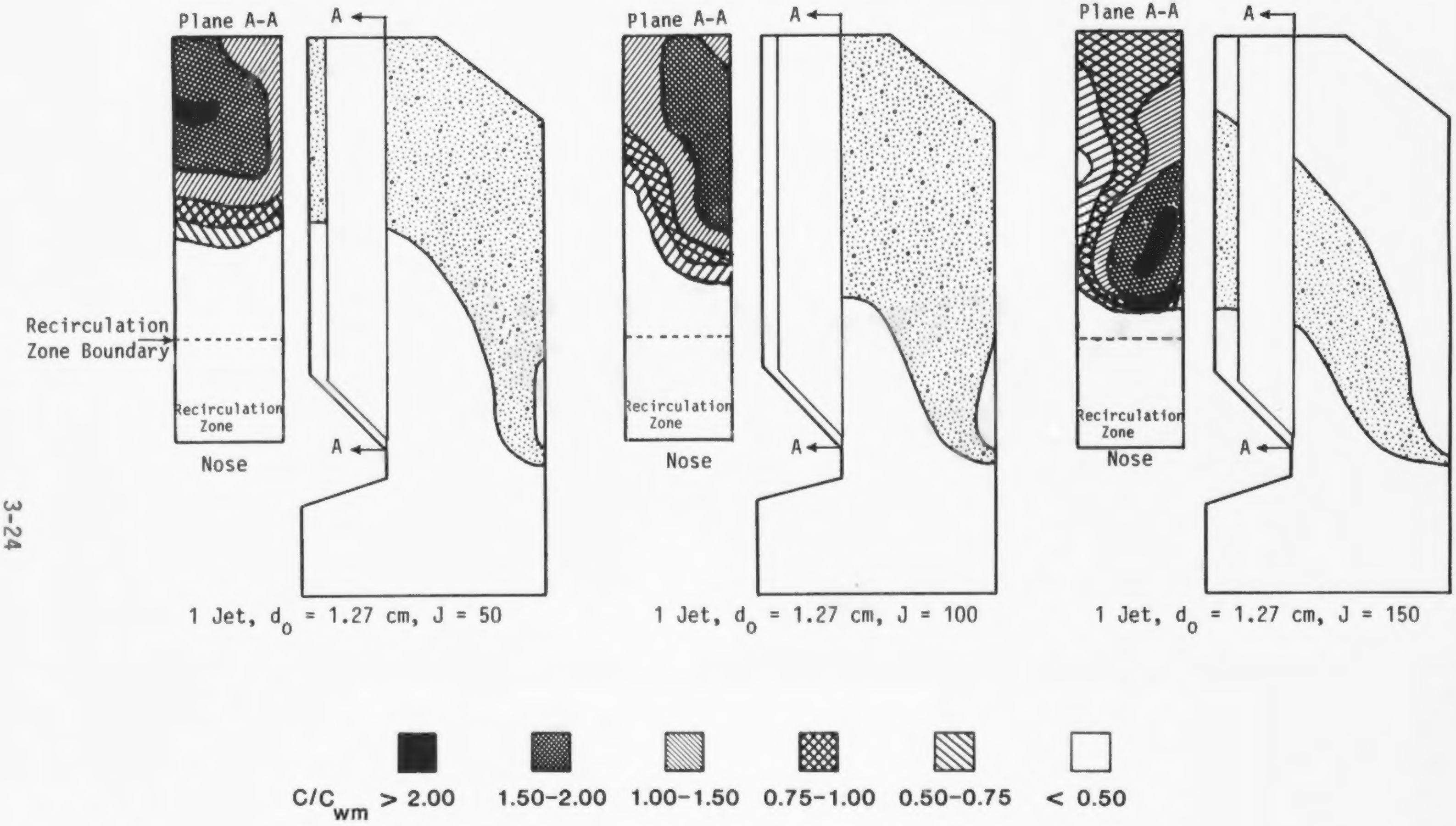
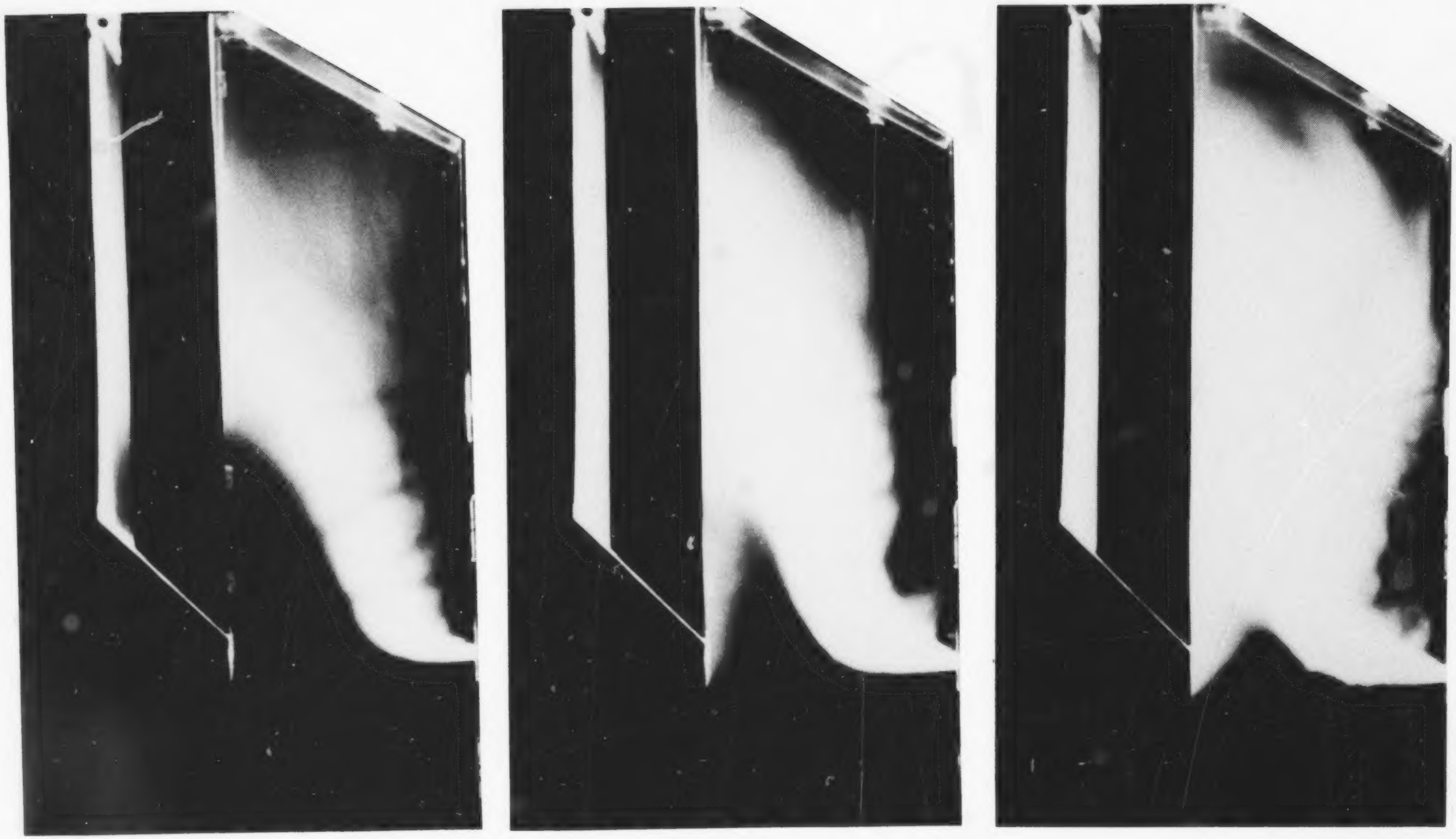
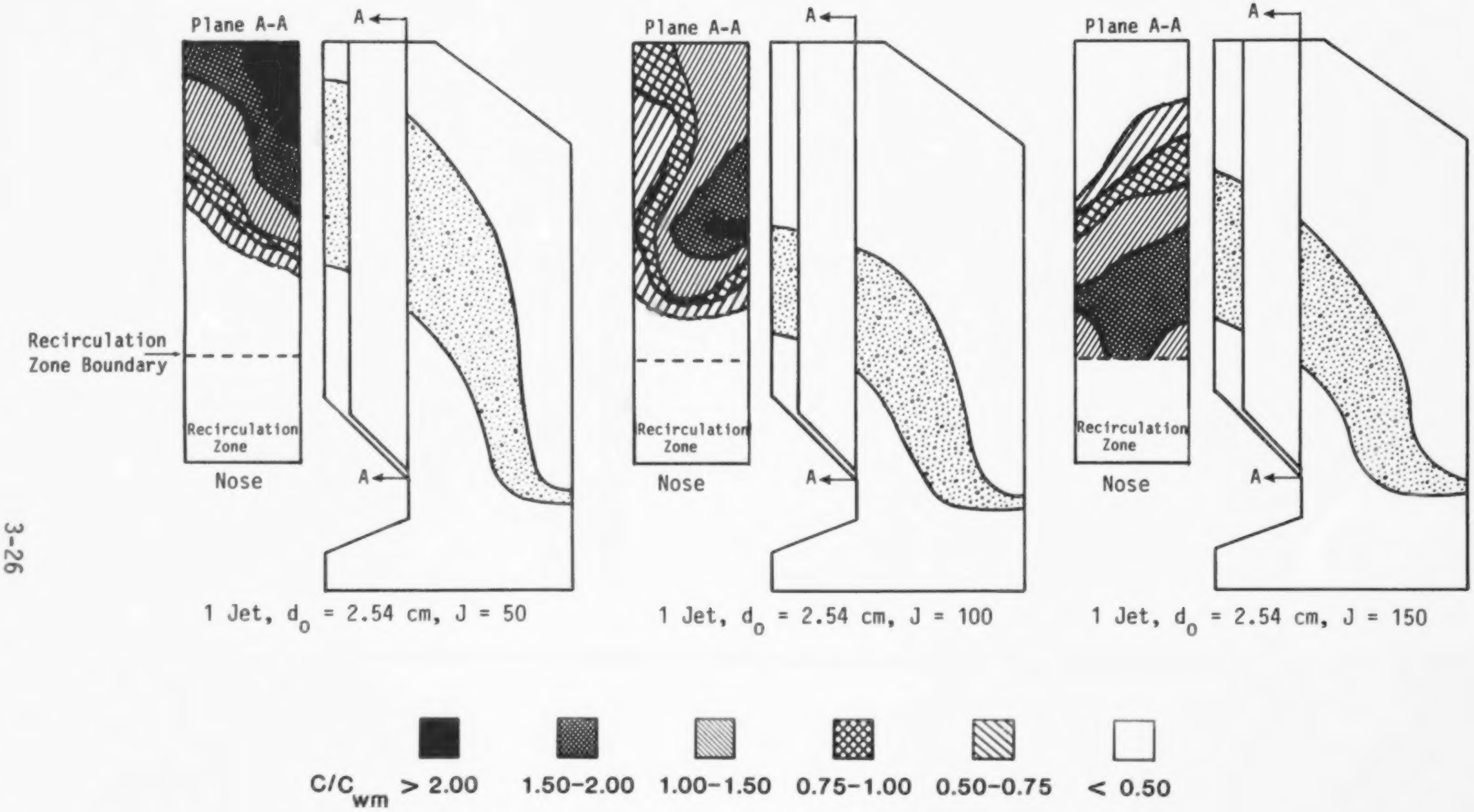

Plane A-A
A
A
Recirculation Zone Boundary
Recirculation Zone
Nose
1 Jet, d_o = 1.27 cm, J = 50
Plane A-A
A
A
Recirculation Zone
Nose
1 Jet, d_o = 1.27 cm, J = 100
Plane A-A
A
A
Recirculation Zone
Nose
1 Jet, d_o = 1.27 cm, J = 150
C/C_{wm} > 2.00
1.50-2.00
1.00-1.50
0.75-1.00
0.50-0.75
< 0.50

Figure 3-13. Comparison of smoke traces and concentration profiles for a single jet at three momentum levels injected at the nose level.



J = 50 J = 100 J = 150

Figure 3-14. photographs of 2.54 cm. diameter jets at momentum ratios of 50, 100 and 150.


Plane A-A
A
A
Recirculation Zone Boundary
Recirculation Zone
Nose
C/C$_{wm}$ > 2.00
1.50–2.00
1.00–1.50
0.75–1.00
0.50–0.75
< 0.50

1 Jet, d_o = 2.54 cm, J = 50

1 Jet, d_o = 2.54 cm, J = 100

1 Jet, d_o = 2.54 cm, J = 150

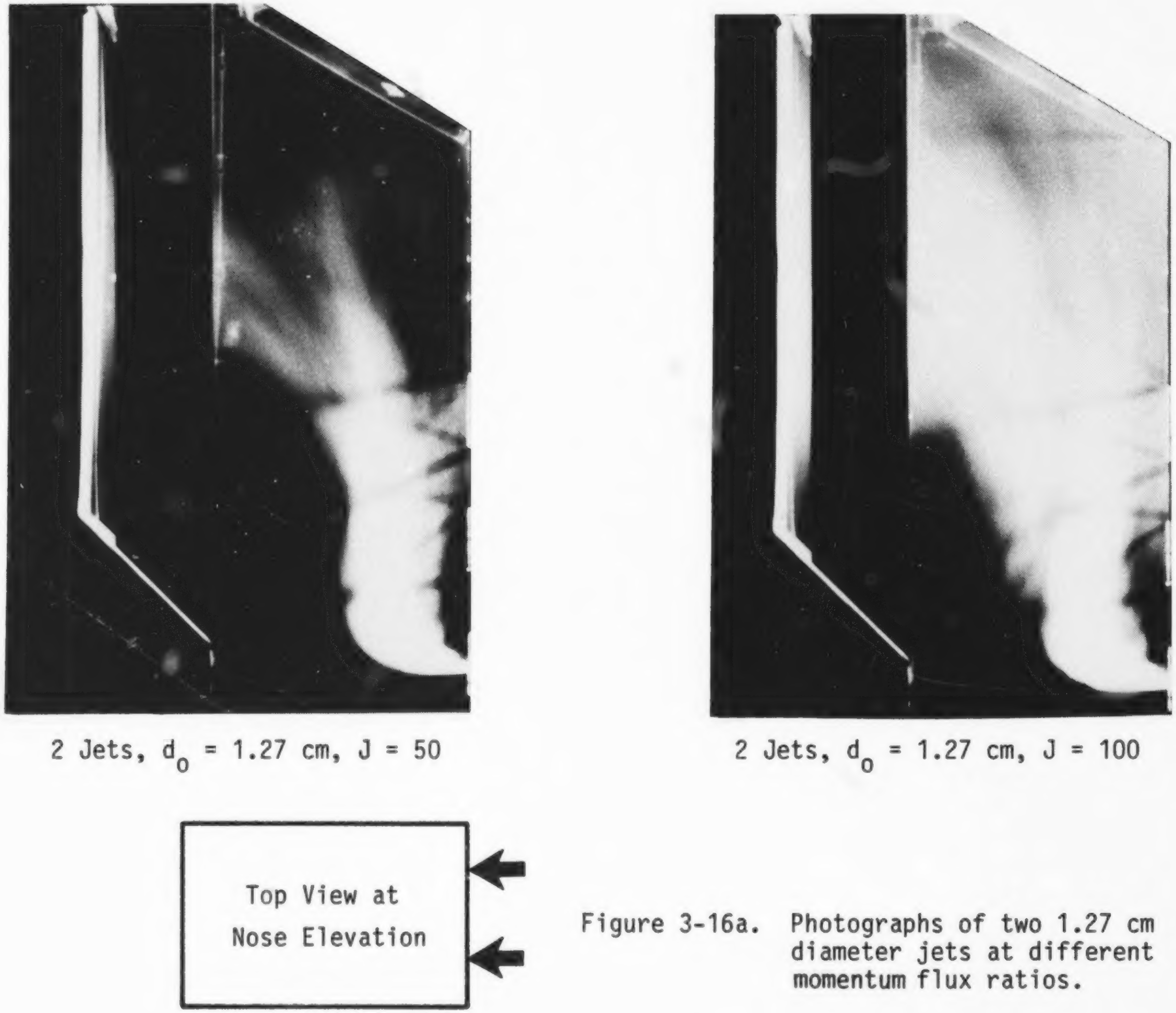
Figure 3-15. Comparison of smoke traces and concentration profiles for a single jet at nose: Effect of jet momentum flux.

Side Spacing

Figures 3-16a and b show smoke photographs of two 1.27 cm diameter jets injected from the front wall at the nose elevation. The two jets were symmetrically located across the width of the model with side spacings (wall-to-jet center) equal half of the spacing between the two jets (center-to-center). Comparison of the dispersion profiles with smoke traces is shown in Figure 3-17. Comparison of these traces with those for a single 1.27 cm diameter jet at the same momentum flux ratio indicate virtually no effect of the side spacing of jets (number of jets in the same row). Side spacing parameter, S/d_0, for the single and two jets were 26.0 and 13.0 respectively. With these large spacing ratios, it is expected that the confinement or restriction imposed by the jets on the cross flow is not sufficient to alter the jet trajectories. Confinement becomes an important factor for closely spaced jets (e.g., $S/d_0 < 10$, see Figure 3-9 for definition). The jet spacing effect is, for example, significant for the closely spaced jets employed in gas-turbine combustors for dilution of combustion products with air before entrance to the turbine section. Confinement effects have been reported by Kamotani & Greber (15) for the dilution jet arrangements encountered in jet engine combustors. The effect of side-spacing is summarized in Figures 3-18 and 3-19. The spacing ratios, S/d_0 of 26.0, 13.0 and 8.7 correspond to 1, 2 and 3 jets respectively. Very little effect of side spacing is seen for 1 and 2 jets. With three jets, the restriction imposed by the jets to the cross flow causes the jets to bend more near the point of injection. In the present study, the injection jets were widely separated so that the confinement effects were not dominant.

Jet Location

Figures 3-20 and 3-21 show the effect of increasing momentum flux ratio on the penetration of a row of two jets injected half of the furnace depth, L, below the nose elevation (see Figure 3-9). Because of the high velocity region in the vicinity of the nose and the direction of the flow (see Figure 3-4), the jets are pushed towards the front wall after the maximum penetration point. Increases in the jet momentum flux increased the

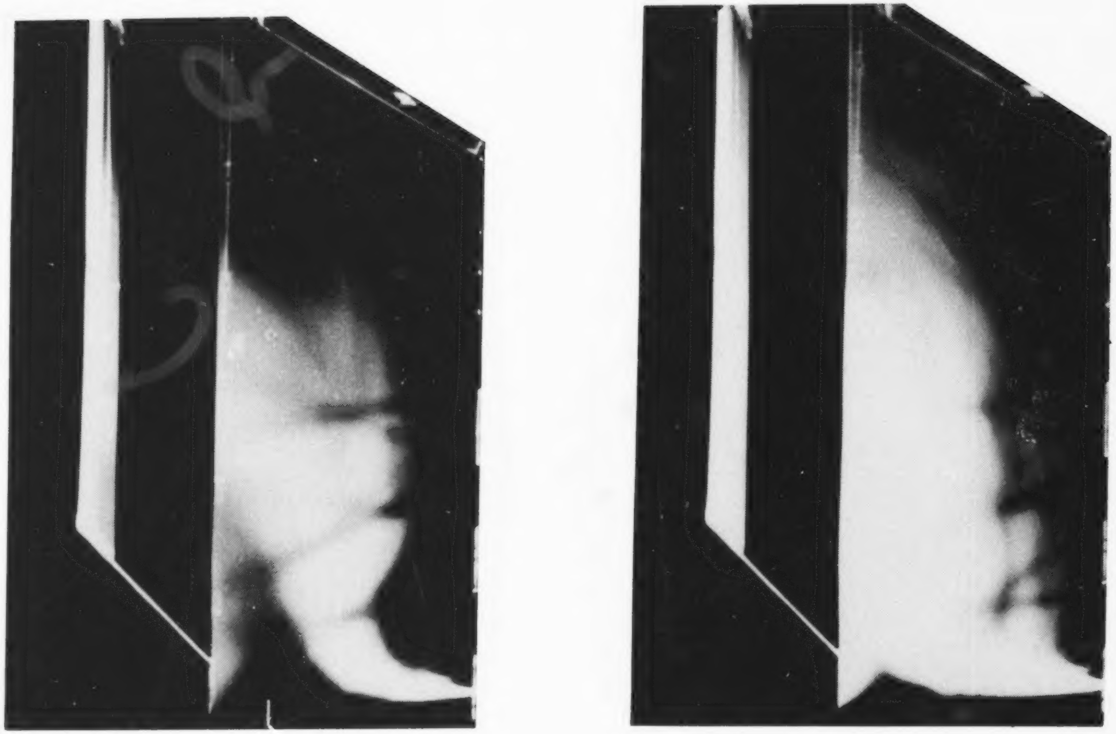


2 Jets, d_o = 1.27 cm, J = 50

2 Jets, d_o = 1.27 cm, J = 100

Top View at
Nose Elevation

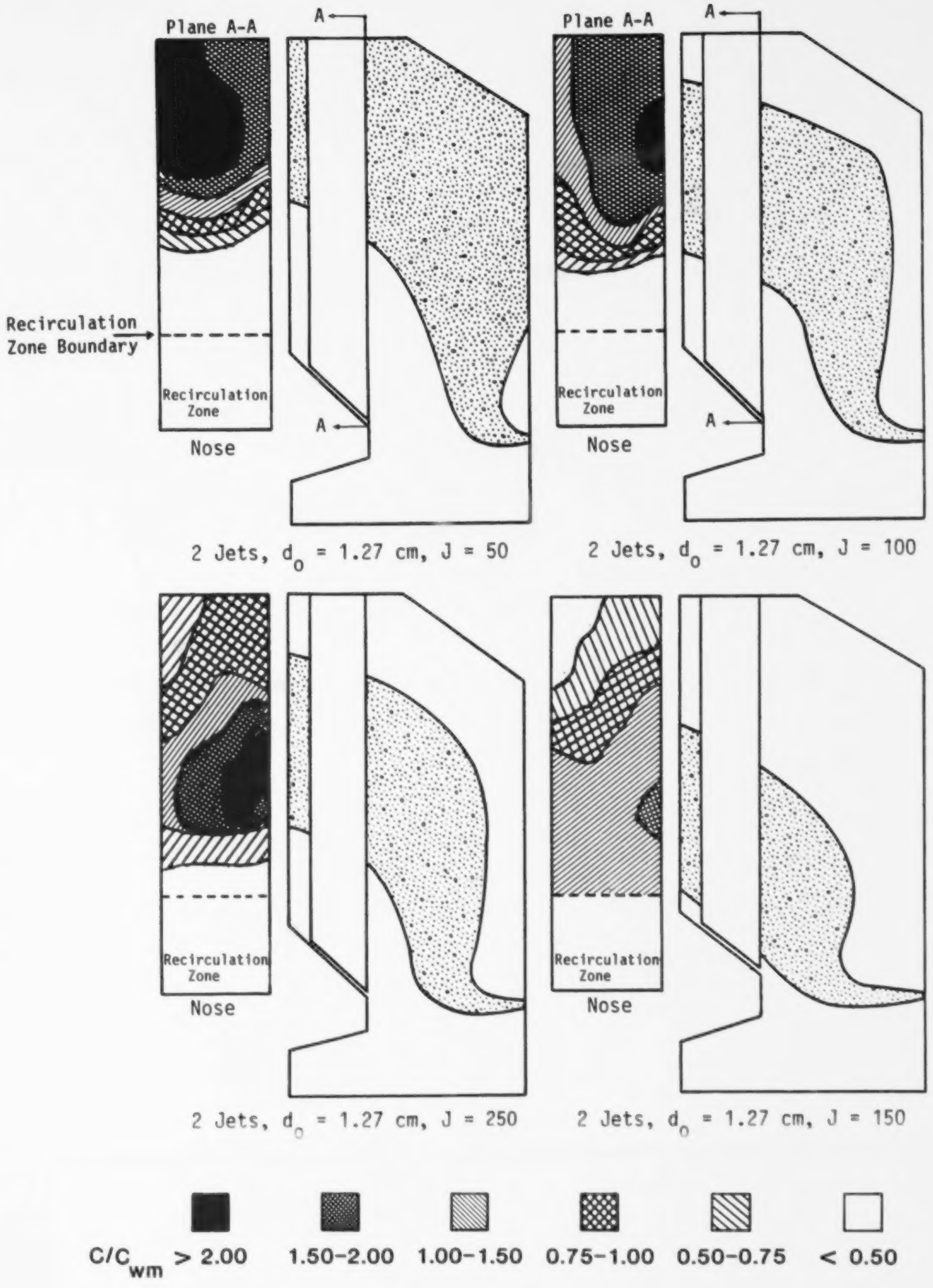
Figure 3-16a. Photographs of two 1.27 cm diameter jets at different momentum flux ratios.



2 Jets, d_o = 1.27 cm, J = 150

2 Jets, d_o = 1.27 cm, J = 250

Figure 3-16b. Photographs of two 1.27 cm. diameter jets at different momentum flux ratios.


Plane A-A
A
A
Recirculation Zone Boundary
Recirculation Zone
Nose
Plane A-A
A
A
Recirculation Zone
Nose
Recirculation Zone
Nose
Recirculation Zone
Nose
C/C$_{wm}$ > 2.00
1.50–2.00
1.00–1.50
0.75–1.00
0.50–0.75
< 0.50

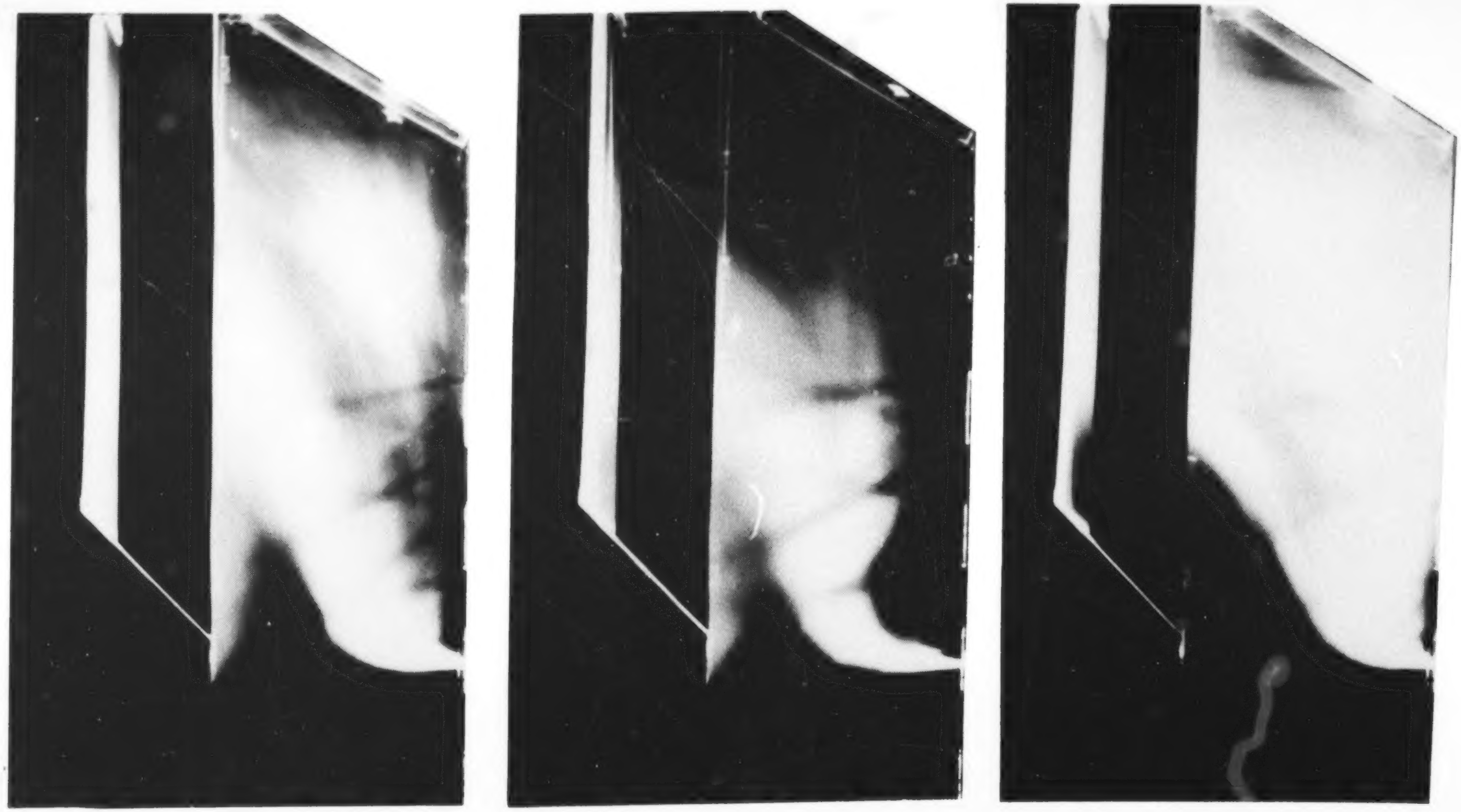
2 Jets, d_o = 1.27 cm, J = 50

2 Jets, d_o = 1.27 cm, J = 100

2 Jets, d_o = 1.27 cm, J = 250

2 Jets, d_o = 1.27 cm, J = 150

Figure 3-17. Comparison of smoke traces and concentration profiles for two jets at nose.



One Jet $S/d_o = 26$ Two Jets $S/d_o = 13$ Three Jets $S/d_o = 8.7$

Figure 3-18. Photographs of 1.27 cm. diameter jets at a momentum flux ratio of 150: effect of jet spacing.

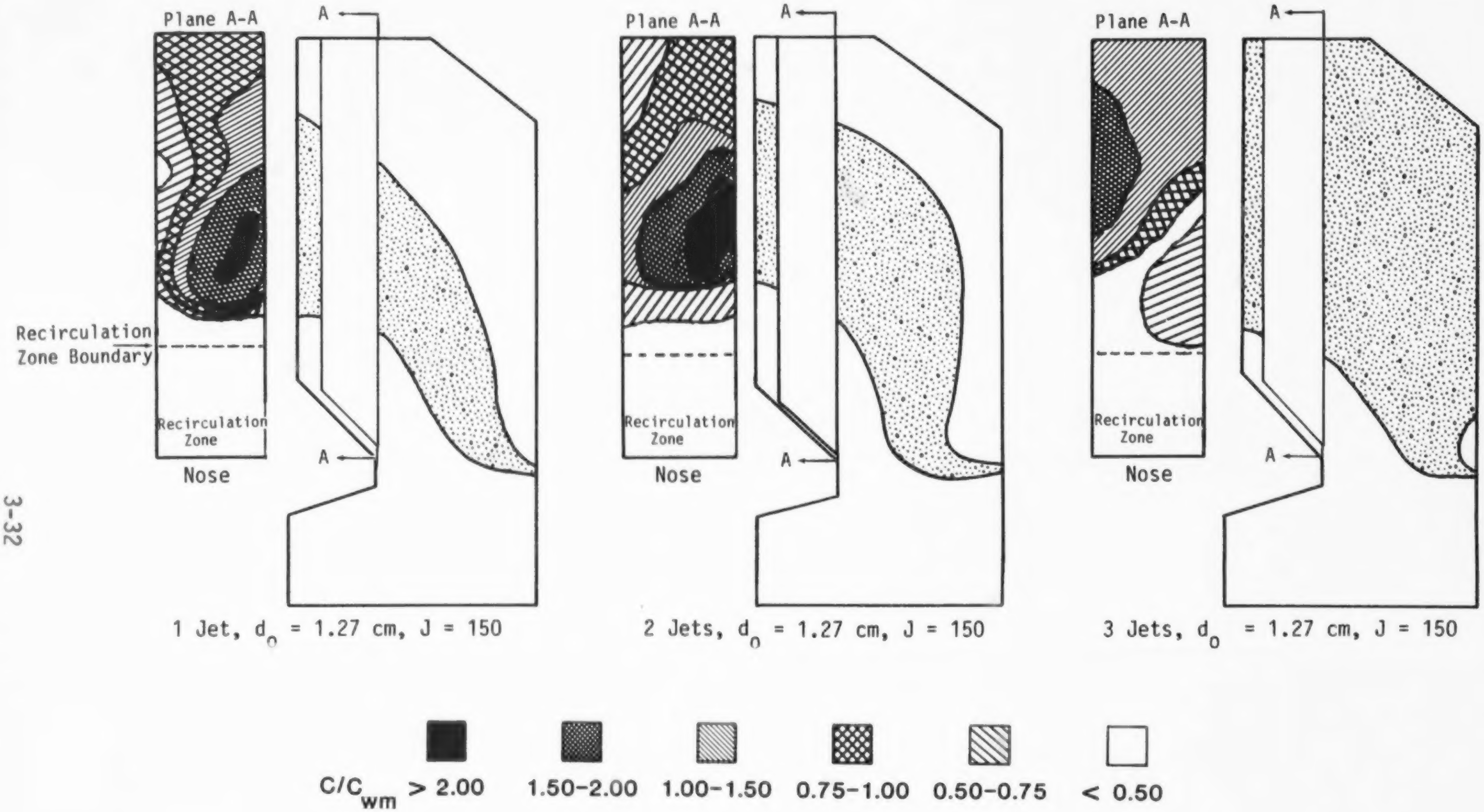
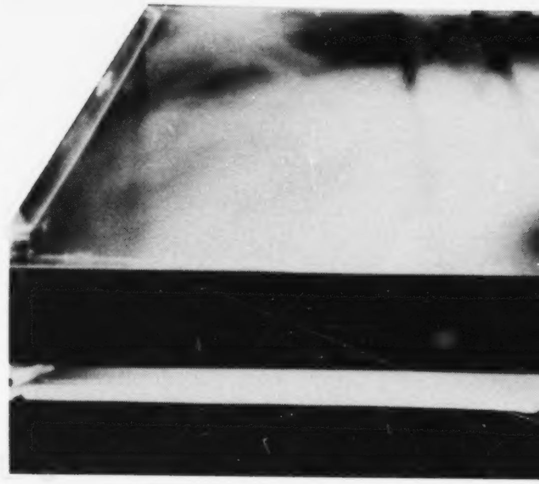
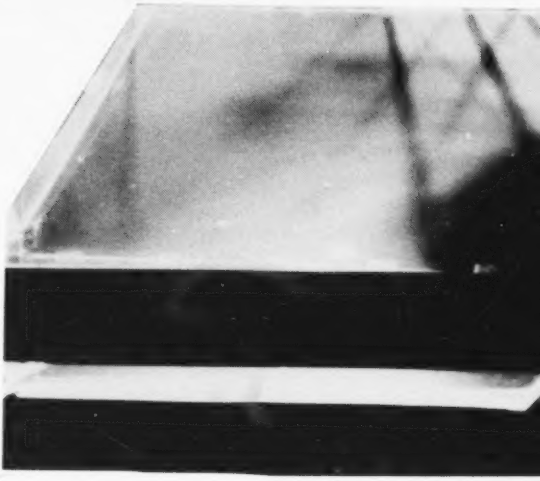
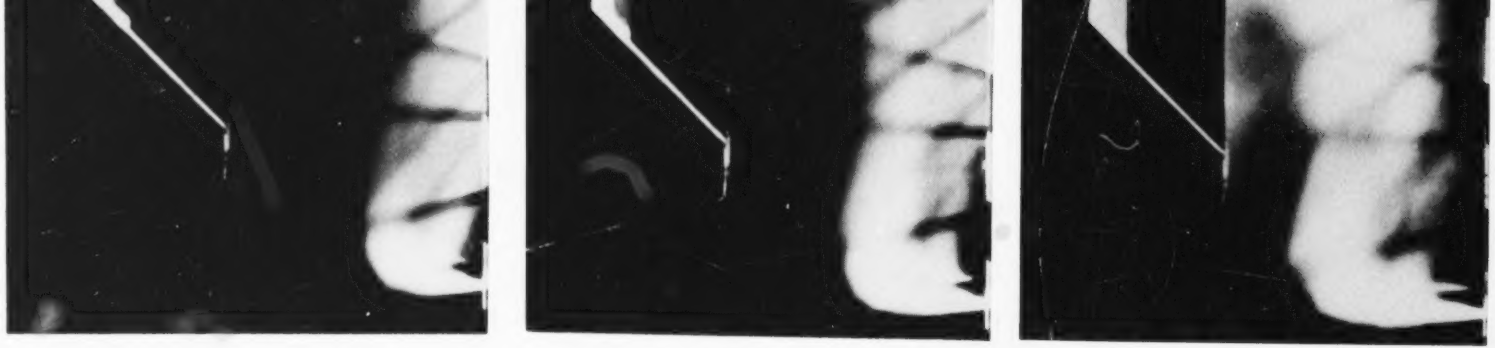

Plane A-A
A
A
Recirculation Zone Boundary
Recirculation Zone
Nose
1 Jet, d_o = 1.27 cm, J = 150
Plane A-A
A
A
Recirculation Zone
Nose
2 Jets, d_o = 1.27 cm, J = 150
Plane A-A
A
A
Recirculation Zone
Nose
3 Jets, d_o = 1.27 cm, J = 150
C/C_{wm} > 2.00
1.50–2.00
1.00–1.50
0.75–1.00
0.50–0.75
< 0.50

Figure 3-19. Comparison of smoke traces and concentration profiles at nose with J = 150: effect of number of jets.





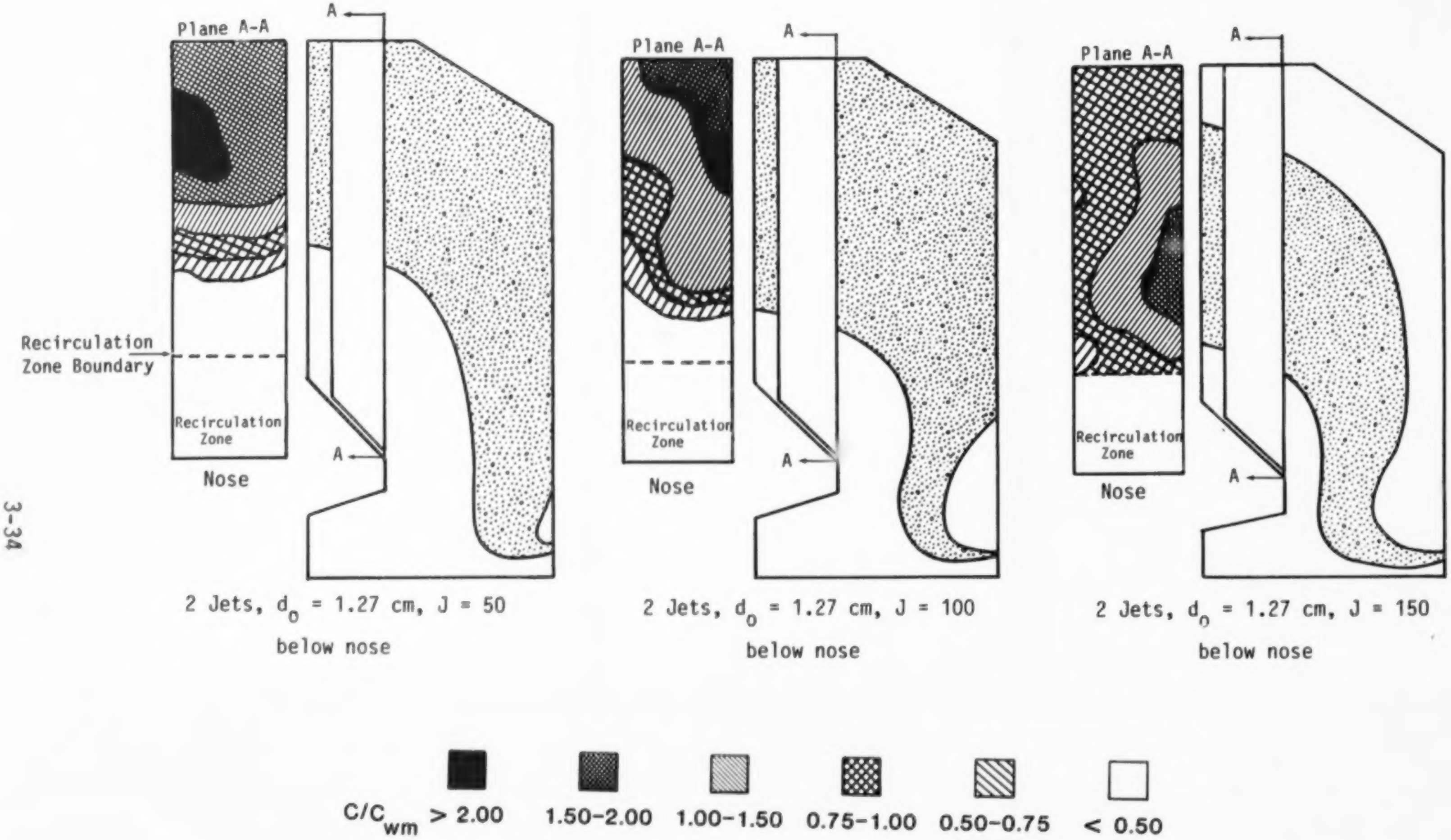


J = 50

J = 100

J = 150

Figure 3-20. Photographs for two 1.27 cm. diameter jets injected below the nose at different momentum flux ratios.



Plane A-A
A
A
Recirculation Zone Boundary
Recirculation Zone
Nose
C/C_{wm} > 2.00
1.50–2.00
1.00–1.50
0.75–1.00
0.50–0.75
< 0.50

2 Jets, d_o = 1.27 cm, J = 50 below nose

2 Jets, d_o = 1.27 cm, J = 100 below nose

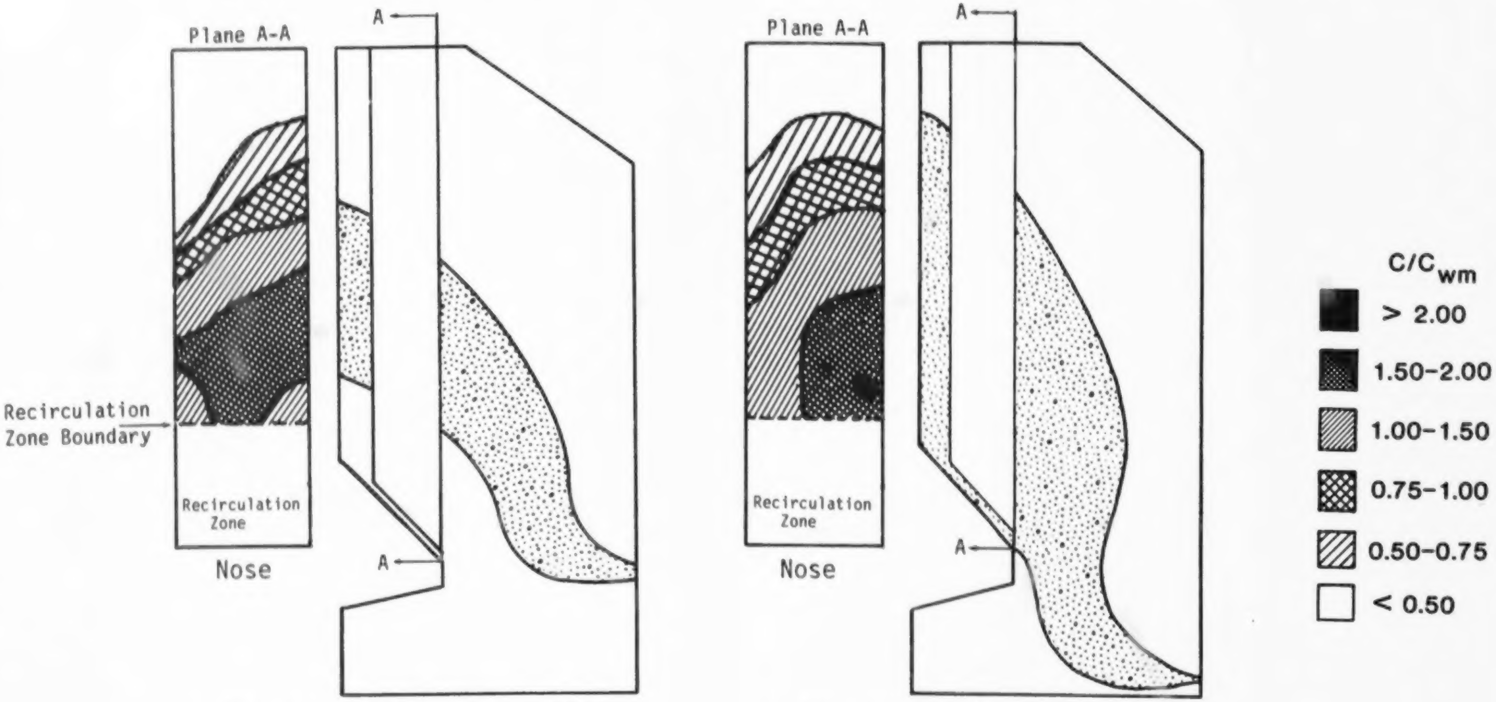
2 Jets, d_o = 1.27 cm, J = 150 below nose

Figure 3-21. Comparison of smoke traces and concentration profiles for two jets below nose: effect of jet momentum.

penetration depth as expected. Comparison of the smoke traces with the dispersion profiles showed the same results as the previous figures. It should be noted that some of the jet fluid is trapped in the recirculation zone for the high momentum jet (J = 150). Effects of the jet location (i.e., injection point) on the dispersion characteristics of a jet in this complex flow field are discussed in the following.

Figure 3-22 shows the smoke traces and the dispersion patterns for a single 2.54 cm diameter jet at J = 150. When the jet is injected at the nose elevation, the jet fluid remains mostly above the recirculation zone boundary. However, when the jet with the same momentum flux is introduced at a lower location (1/2 of the front wall to nose point distance below the nose level injection elevation), the jet penetration changes and some of the jet fluid is trapped in the recirculation zone. A more complete examination of the jet location on the front wall is given in Figure 3-23 for two jets at a momentum flux ratio of 150. In relation to the jets located at the nose plane (center figure), the jets which were half the duct depth above the nose plane experience less of the cross flow and penetrate across to the superheater inlet. On the other hand, the jets located below the nose are turned back by the cross flow and some of the jet fluid is trapped in the recirculation zone. Figure 3-24 shows two jets injected approximately one duct depth above the nose plane. Since these jets are in a lesser field of cross flow and travel straight across, the influence of jet momentum flux was quite small.

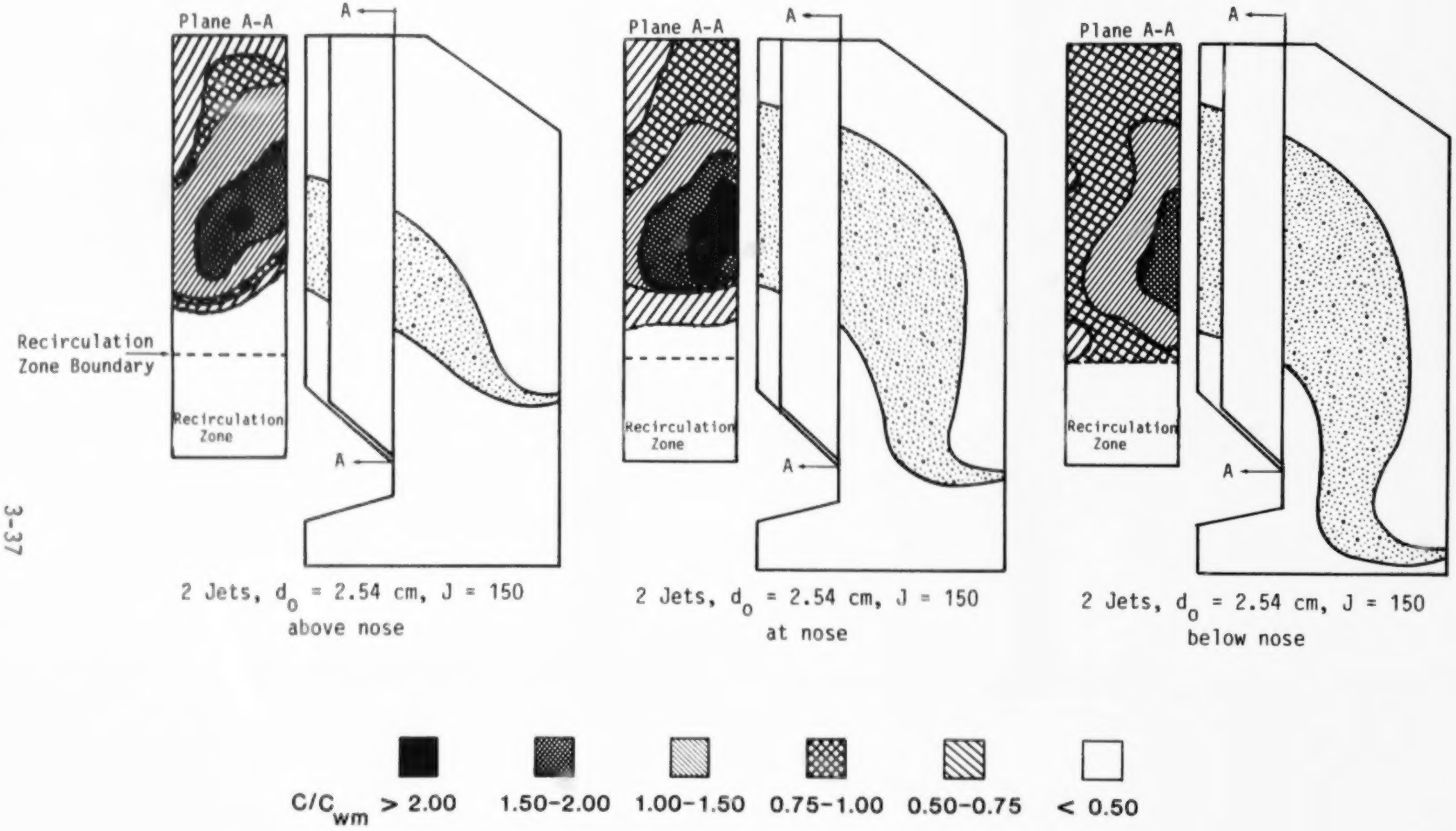
So far, the injection of jets from the front wall were considered since it is one of the most likely injection options for wall fired boilers. However, other possibilities for injection exist in other parts of the boiler. One option is to introduce sorbent near the high velocity regions where most of the furnace mass flow is concentrated. This prompted some investigation with jets located at the nose constriction, although in many boilers this region is inaccessible. Figure 3-25 shows smoke traces for a single, 1.27 cm diameter jet at momentum flux ratios of 50, 100, 150 and 250. Although reasonable jet penetration and dispersion can be obtained with this


Plane A-A
A
A
Recirculation Zone Boundary
Recirculation Zone
Nose
Plane A-A
A
A
Recirculation Zone
Nose
C/C_{wm}
> 2.00
1.50-2.00
1.00-1.50
0.75-1.00
0.50-0.75
< 0.50

1 Jet, d_o = 1.54 cm, J = 150
At Nose

1 Jet, d_o = 2.54 cm, J = 150
Below Nose

Figure 3-22. Comparison of smoke traces and concentration profiles for one jet: effect of jet location.


Plane A-A
A
Recirculation Zone Boundary
Recirculation Zone
C/C_{wm} > 2.00
1.50-2.00
1.00-1.50
0.75-1.00
0.50-0.75
< 0.50

2 Jets, d_o = 2.54 cm, J = 150
above nose

2 Jets, d_o = 2.54 cm, J = 150
at nose

2 Jets, d_o = 2.54 cm, J = 150
below nose

Figure 3-23. Comparison of smoke traces and concentration profiles for two jets below nose: effect of jet momentum.

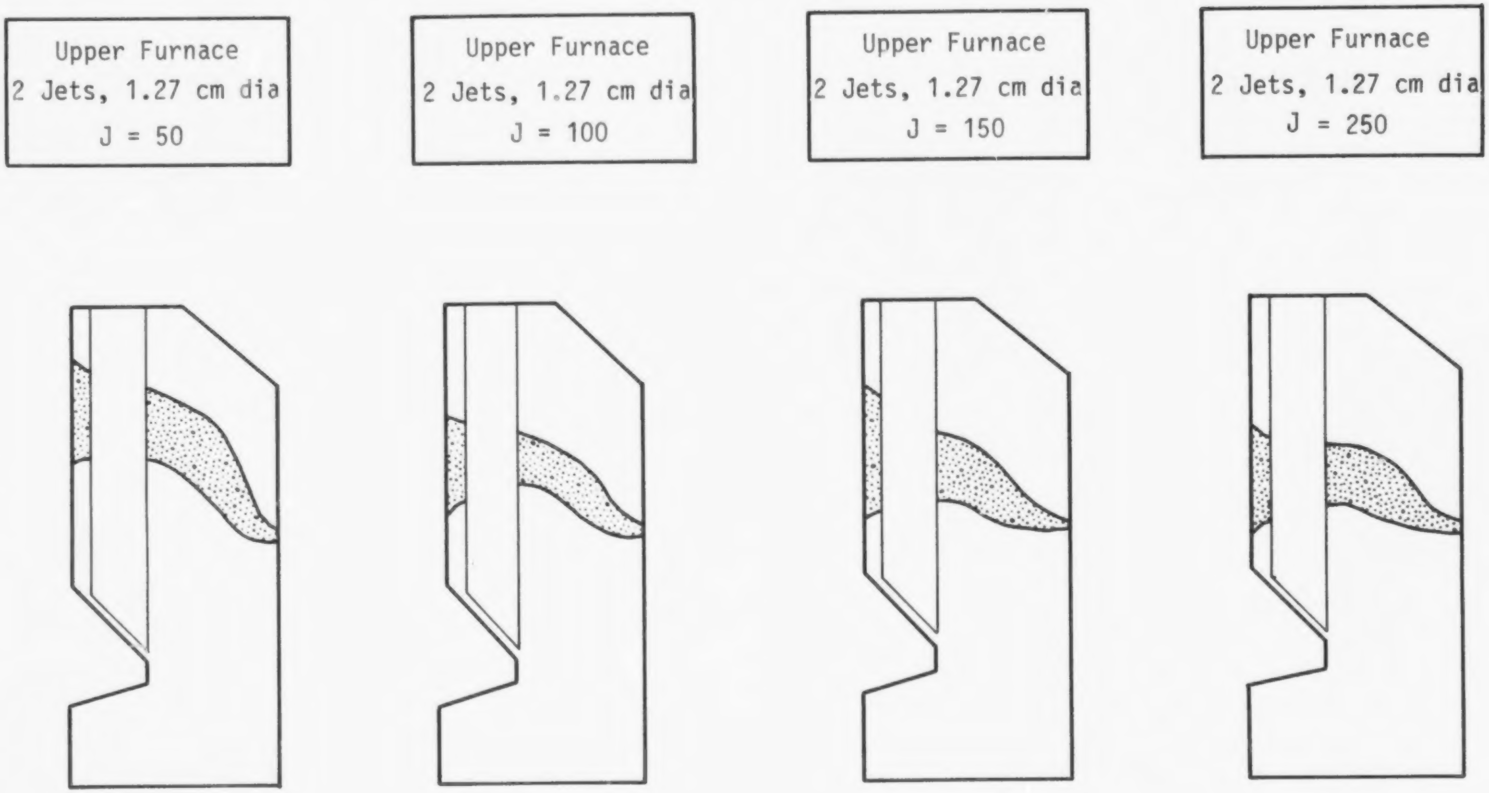

Upper Furnace
2 Jets, 1.27 cm dia
J = 50
Upper Furnace
2 Jets, 1.27 cm dia
J = 100
Upper Furnace
2 Jets, 1.27 cm dia
J = 150
Upper Furnace
2 Jets, 1.27 cm dia
J = 250

Figure 3-24. Smoke traces for two 0.5 inch diameter jets injected above the nose: effect of jet momentum flux.

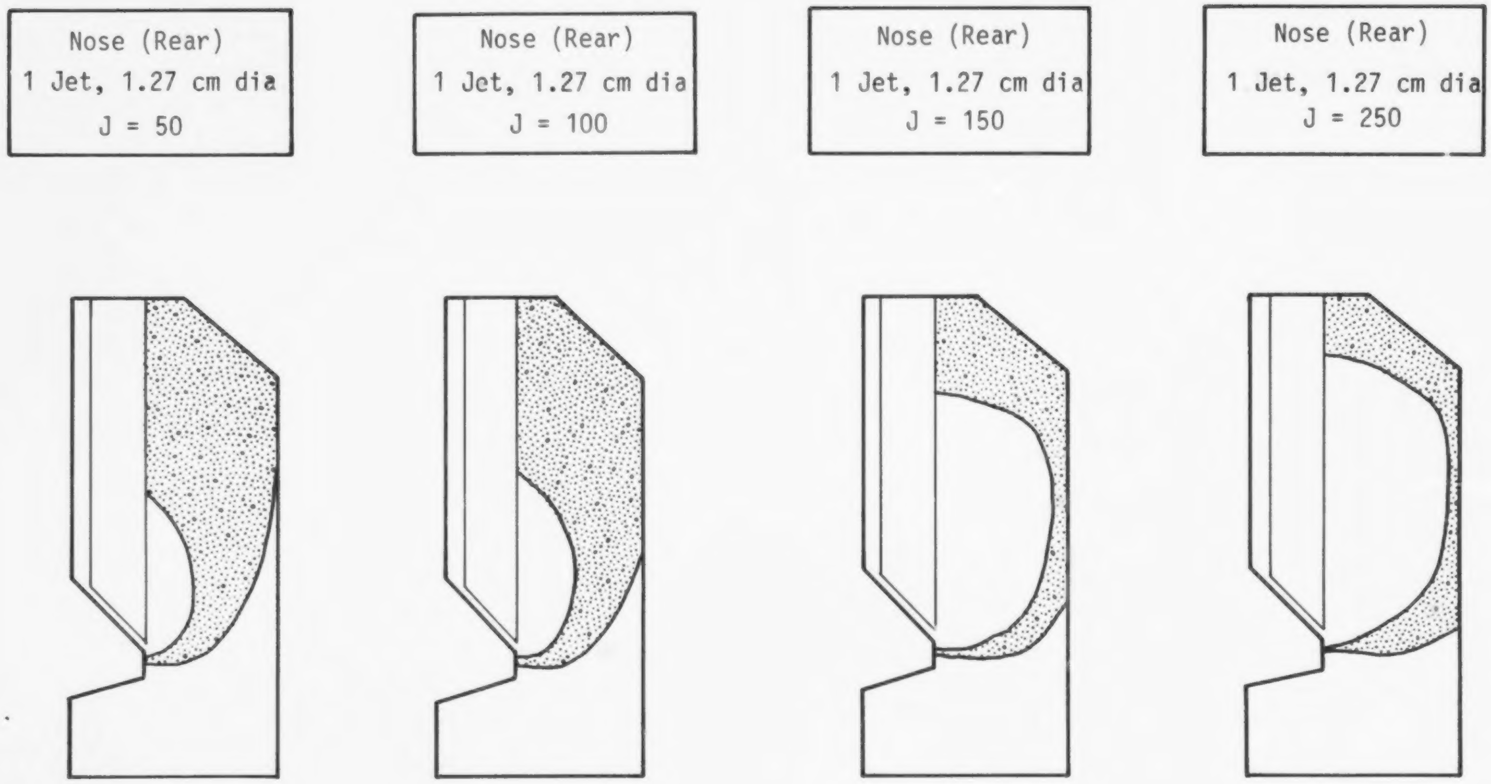

Nose (Rear)
1 Jet, 1.27 cm dia
J = 50
Nose (Rear)
1 Jet, 1.27 cm dia
J = 100
Nose (Rear)
1 Jet, 1.27 cm dia
J = 150
Nose (Rear)
1 Jet, 1.27 cm dia
J = 250

Figure 3-25. Rear wall jet injection at the nose plane.

scheme, entrapment of some of the jet fluid into the recirculation zone is inevitable.

Another possibility is to inject from the roof of the boiler. This may avoid exposure of the sorbent to high temperatures and provide some additional residence time for sulfation. Screening tests were conducted to evaluate the feasibility of this approach although again, in some boilers, the roof may not be accessible. Figure 3-26 shows the behavior of a single 1.27 cm diameter jet injected from the roof. The jet penetration increases as the jet momentum is raised. In order to obtain jet penetration to the nose plane, the jet momentum flux has to be considerably high. This diminishes the gain in the residence time because of the very high velocities offsetting the gain in the path length. A more in-depth discussion of roof injection is given in Section 8.0 of this report.

3.2.4 Particle-Laden Jets

The experiments on jet injection and dispersion, described above, were based on isothermal modeling of gas jets simulating particle laden jets. The assumption was made that the sorbent particles are small (less than 20 μm mass mean size) so that the effect of the particles can be expressed in the jet parameters. Hence, the influence of small particles is incorporated in the density and the momentum of the jet fluid as follows:

$$\rho_j = \rho_{air} (1 + x) \qquad \text{where } x = \frac{\dot{M}_{sorbent}}{\dot{M}_{air}} \tag{3-3}$$

and

$$J = \frac{\rho_j V_j^2}{\rho_\infty V_\infty^2} \tag{3-4}$$

Figure 3-27 shows the validity of this assumption by comparison of a particle laden jet seeded with Vicron 45-3 $CaCO_3$ particles (size range: 3 to 45 μm, mass mean size: 10 μm) and the equivalent air jet. The studied case was 0.59 cm diameter jet at a momentum flux ratio of 100 injected at the nose

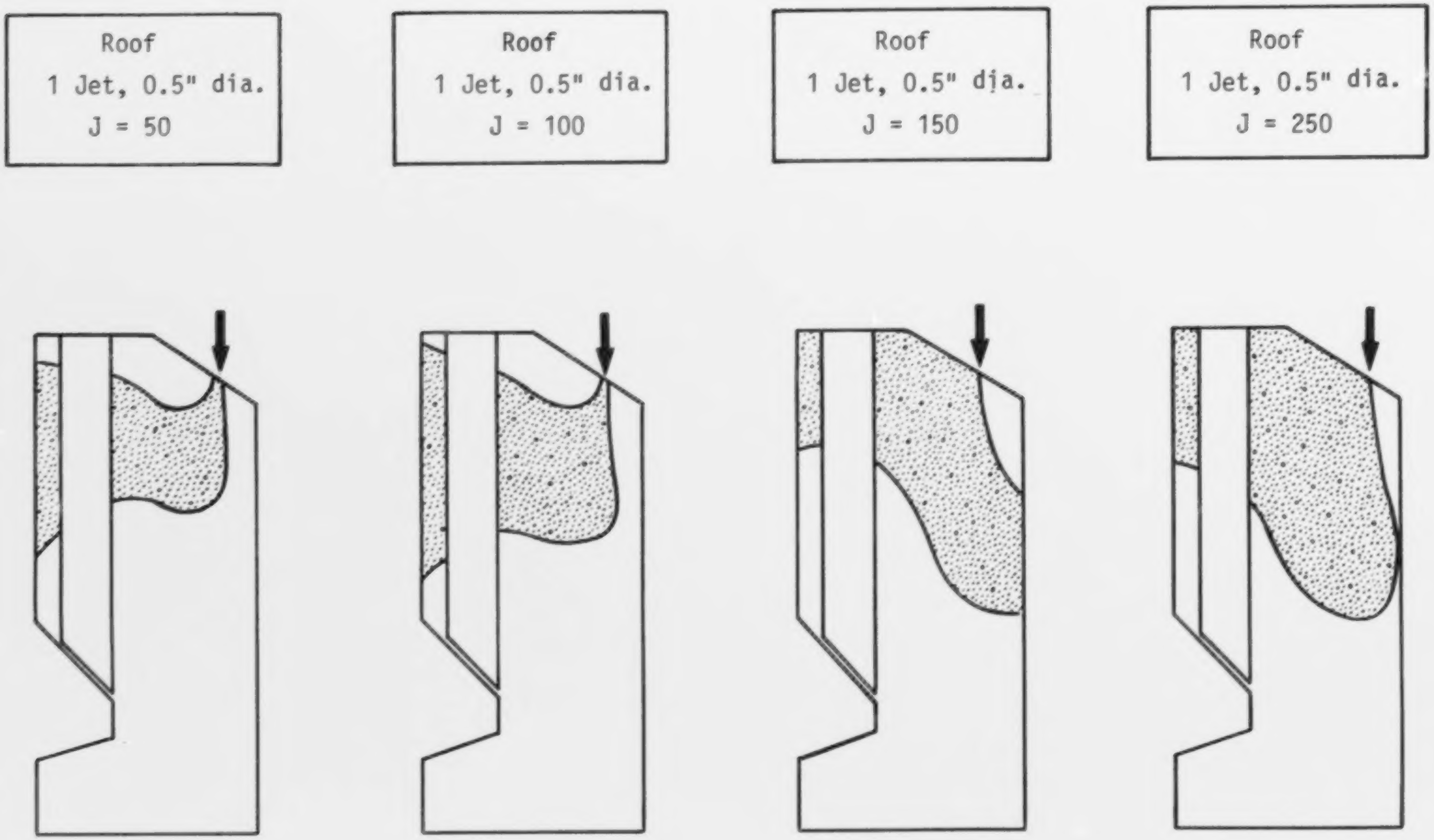
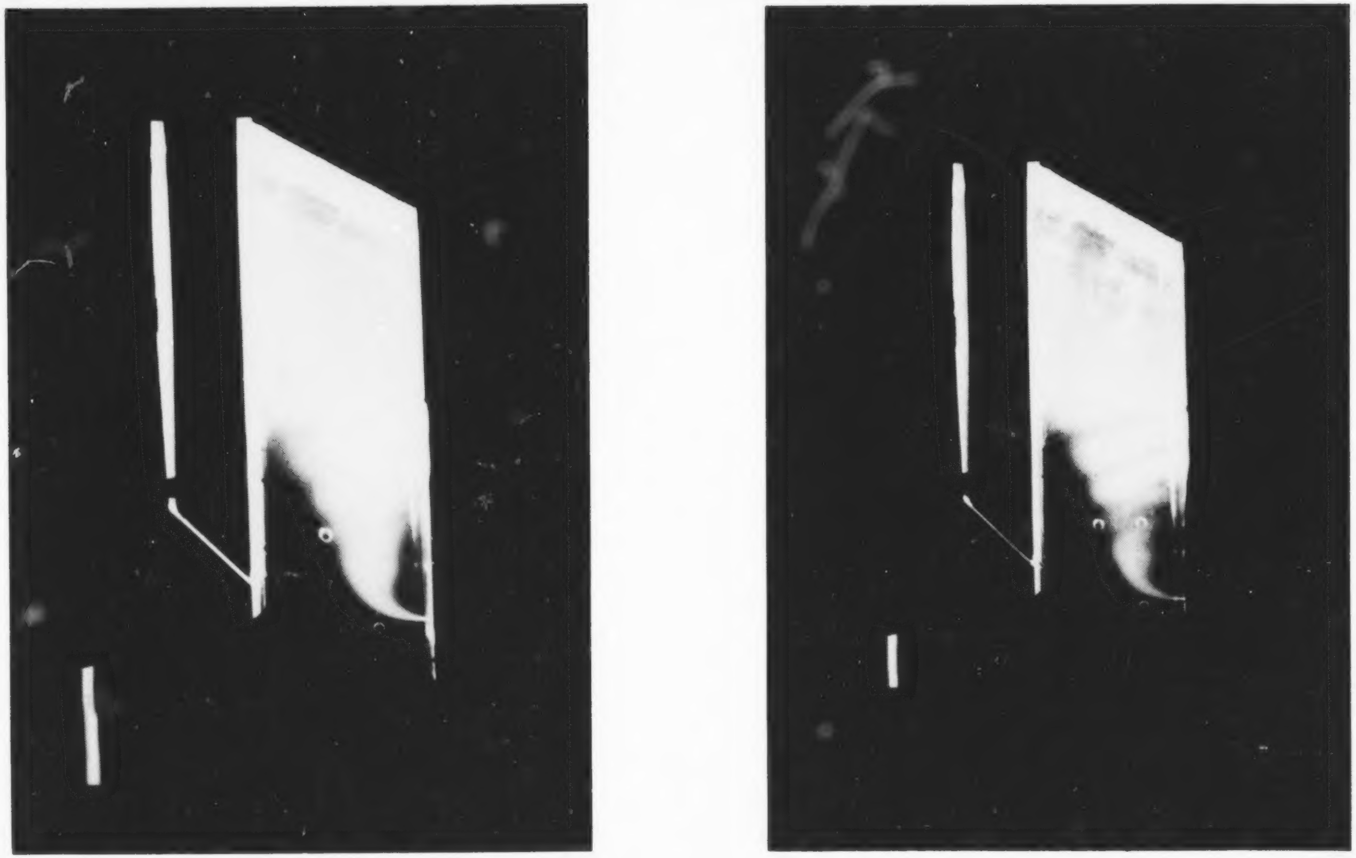

Roof
1 Jet, 0.5" dia.
J = 50
Roof
1 Jet, 0.5" dia.
J = 100
Roof
1 Jet, 0.5" dia.
J = 150
Roof
1 Jet, 0.5" dia.
J = 250

Figure 3-26. Examples of roof injection.



Smoke Particle

Figure 3-27. Comparison of smoke tracer and particle jet visualization of eight jets spaced across the model width at the nose elevation on the front wall. Jet to cross flow momentum ratio, J = 100, $\dot{M}_{sorbent}/\dot{M}_{air}$ = 0.16.

elevation on the front wall. The solids loading ratio in the jet was approximately 0.16, corresponding to a Ca/S molar ratio of 2 for the operating conditions of the Edgewater boiler described in Section 8.0. The jet velocity was adjusted to compensate for the increased jet density by particles. In the particle laden jet, jet visualization was achieved by the light scattered by the sorbent particles. It was observed that there were no appreciable differences in the penetration and spread characteristics of the two jets, indicating that smoke visualization and gas tracer studies are good simulations of sorbent particle behavior for small particle size. This observation was in accordance with the calculations performed for the inertial behavior of particles in a gas stream. However, the behavior of large particles could be significantly different as discussed in the following.

3.2.4.1 Particles in Jets

The behavior of sorbent particles in injection jets can be estimated for lightly-loaded jets. For this purpose, simple particle dynamics can be considered to determine the particle relaxation times and distances in a free turbulent jet. For dilute jets, the equation of motion governing the particle motion can be written as:

$$m_p \frac{dV_p}{dt} = 3\pi\mu d_p (V - V_p) \qquad (3\text{-}5)$$

where: m_p is the mass of sorbent particle

V_p is the particle speed

μ is the viscosity in the jet

V is the velocity in the jet given by $4.8\ V_j d_j / x$ and x is the distance along the jet.

Equation 3-5 can be simplified to

$$A \frac{du}{d\zeta} = \frac{4.8}{u\zeta} - 1 \qquad (3\text{-}6)$$

where: $A = \frac{\tau V_o}{d_o}$, $\tau = \frac{1}{18} \frac{\rho_p \, d_p{}^2}{\mu}$, $u = \frac{V_p}{V_o}$ and $\zeta = \frac{x}{d_o}$

Typical values of τ and A for a jet with V_o = 30.5 m/s, d_o = 20.3 cm at 27°C were computed for different particle diameters. The results are shown in Table 3-3. Unfortunately, equation (3-6) does not provide an analytical solution. It was numerically integrated for two values of A. The results, shown in Figure 3-28, reveal the behavior of different size particles (characterized by the values of A) in a simple jet. The behavior exhibited by large particles (A=5) indicate that they retain their velocities down to 15 jet diameters while the jet velocity continues to decay. However, further downstream, the particles start to slow down and finally come into equilibrium with the gas flow. Similar effects are observed for smaller particles (A=1), but the particles reach equilibrium with gas flow considerably sooner. Based on this picture, it can be stated that large particles in the jet behave more independently of the jet than the small particles. This argument was confined to behavior of particles in a straight jet. In the case of a particle laden jet in cross-flow, the larger particles will tend to leave the jet as it turns. However, for sorbent particles with majority less than 20 μm in size, the particles will relax to the local gas velocities in a few jet diameters downstream from the injection point. This is in confirmation of the experimental observations, indicating the similarity of the jet trajectories and spread as well as the analysis given below.

3.2.4.2 Behavior of Particles in Turning Flows

Particles injected into a boiler gas flow travel along paths which diverge from the gas paths because of their higher inertia. Under steady conditions, the particle acquires a velocity relative to the gas where the

TABLE 3-3. PARTICLE-JET PARAMETERS

Particle Size d_p, μm	τ, sec	A
1 μm	1×10^{-5}	1.5×10^{-3}
10 μm	8×10^{-4}	0.12
20 μm	3×10^{-3}	0.45
50 μm	2×10^{-2}	3.0

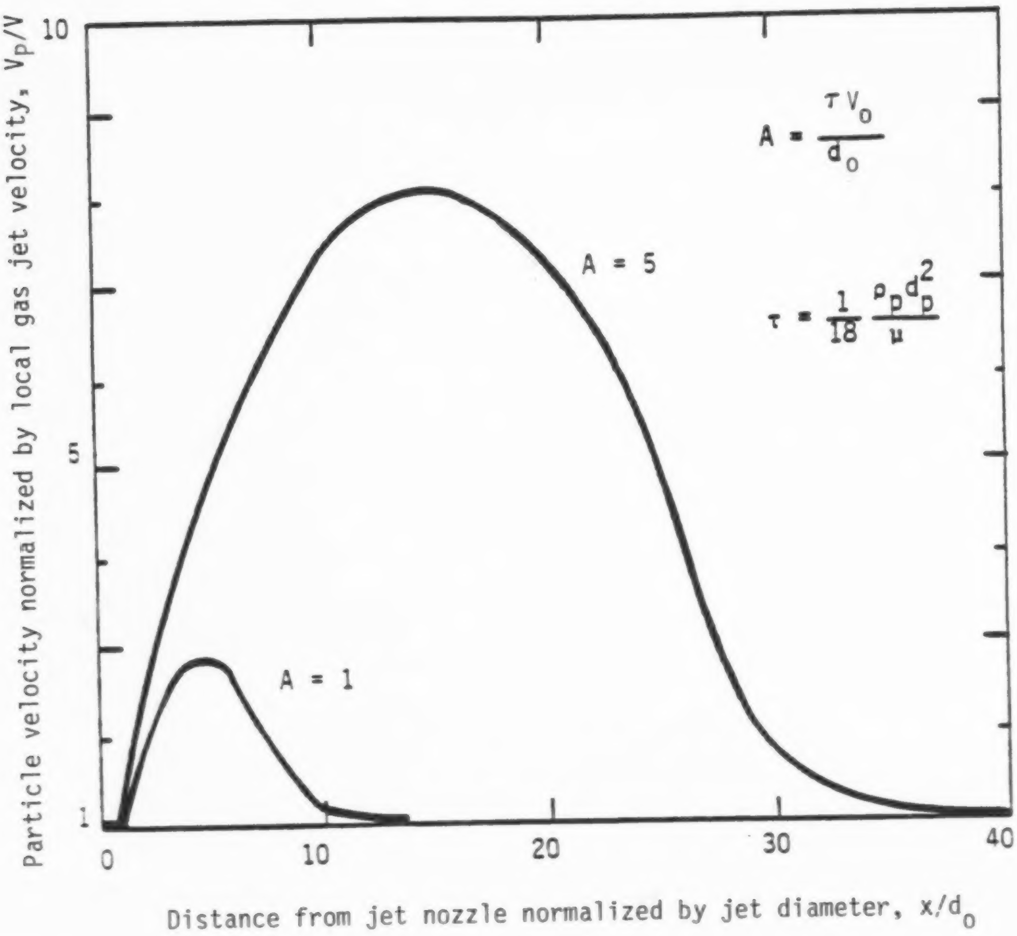


Figure 3-28. Particle speeds in a free jet.

aerodynamic drag force is equal to the particle inertia force. If we consider a particle in a gas moving at velocity V_t around a circular path of radius R, and assume that the particle relative velocity is low enough for its drag coefficient to follow Stoke's Law (16), the radial velocity of the particle is:

$$\frac{V_r}{V_t} = \frac{\sigma d^2 V_t}{18 \mu g R} \tag{3-7}$$

where V_r is the radial component of velocity,

V_t is the tangential component of velocity,

σ is the particle density,

μ_g is the gas viscosity, and

R is the radius of curvature of particle path.

For small particles which have a low terminal velocity in a flow with small acceleration in the tangential direction, the tangential velocity of the particle will be close to the gas velocity and by substituting and rearranging equation (3-7) the particle velocity relative to the gas velocity becomes:

$$\frac{V_r}{V_g} = \frac{1}{18} \cdot \left(\frac{\sigma}{\rho}\right) \cdot \left(\frac{d^2}{L}\right) \cdot \left(\frac{L}{R}\right) \cdot \quad Re \tag{3-8}$$

where L is the duct dimension,

Re is the Reynolds Number based on duct conditions, and

ρ is the gas density.

For particles in a model to have geometrically similar paths to particles in a prototype flow,

$$\left(\frac{V_r}{V_g}\right)_m = \left(\frac{Vr}{V_g}\right)_p \tag{3-9}$$

which will be achieved if the non-dimensional groups in equation (3-8) are kept the same between model and prototype. Thus, the diameter of a model particle with the same trajectory as the prototype particle in a geometrically similar flow is given by

$$\left(\frac{d_m}{d_p}\right)^2 = \frac{\sigma_p}{\sigma_m} \cdot \frac{\rho_m}{\rho_p} \cdot \left(\frac{L_m}{L_p}\right)^2 \cdot \frac{Re_p}{Re_m} \tag{3-10}$$

Considering the Edgewater isothermal model in comparison with the full scale boiler, the following data applies:

$\sigma_p = 1.67 \times 10^3$ kg/m^3 (calcium oxide particles, porosity 50%),
$\sigma_m = 2.70 \times 10^2$ kg/m^3 (limestone particles, porosity 0%),
$\rho_m = 1.23$ kg/m^3 (air at STP),
$\rho_p = 0.23$ kg/m^3 (flue gas at 1300°C),
$\frac{L_m}{L_p} = \frac{1}{7}$ (geometric scale factor),
$Re_p = 230{,}000$ (based on velocity and depth at boiler nose), and
$Re_m = 51{,}000$ (based on velocity and depth at model nose).

This gives the model particle size as

$$\frac{d_m}{d_o} = 0.55 \tag{3-11}$$

i.e. 10 μm limestone particles in the model are equivalent to 55 μm calcium oxide particles in the prototype.

We can also make an estimate of the rate of divergence of the particles across the flow using equation (3-8). The radius of curvature of the flow R is not known, but will be of the order of the duct or model dimension L. Hence the radial velocity of 10 μm diameter particles is of the order of:

$$\left(\frac{V_r}{V_g}\right)_m = 0.013 \text{ for the model and } \left(\frac{V_r}{V_g}\right)_p = 0.0027 \text{ for the prototype} \qquad (3\text{-}12)$$

which is small for both cases, and thus these particles can be expected to follow the gas streamlines with small divergence.

Particle Concentration Measurements

During the isothermal tests, measurements of particle dispersion were attempted using a laser-extinction technique. These measurements were intended to provide a qualitative picture rather than to determine absolute particle number densities. The technique was based on the attenuation of a monochromatic light beam due to scattering and absorption of light by the particles. Figure 3-29 shows the schematic of the probe designed to make these measurements.

The principle of solid concentration measurements is based upon detection of relative extinction of a light beam passing through a particle cloud. This extinction can be represented mathematically by Beer's Law as,

$$\frac{I_0}{I_I} = e^{-K\,L} \qquad (3\text{-}13)$$

where: L is the path length shown in Figure 3-30
I_I is the incident light intensity
I_0 is the attenuated light intensity

and K can be written as

$$K = \int_{r=0}^{\infty} k(r)\, N(r)\, dr \qquad (3\text{-}14)$$

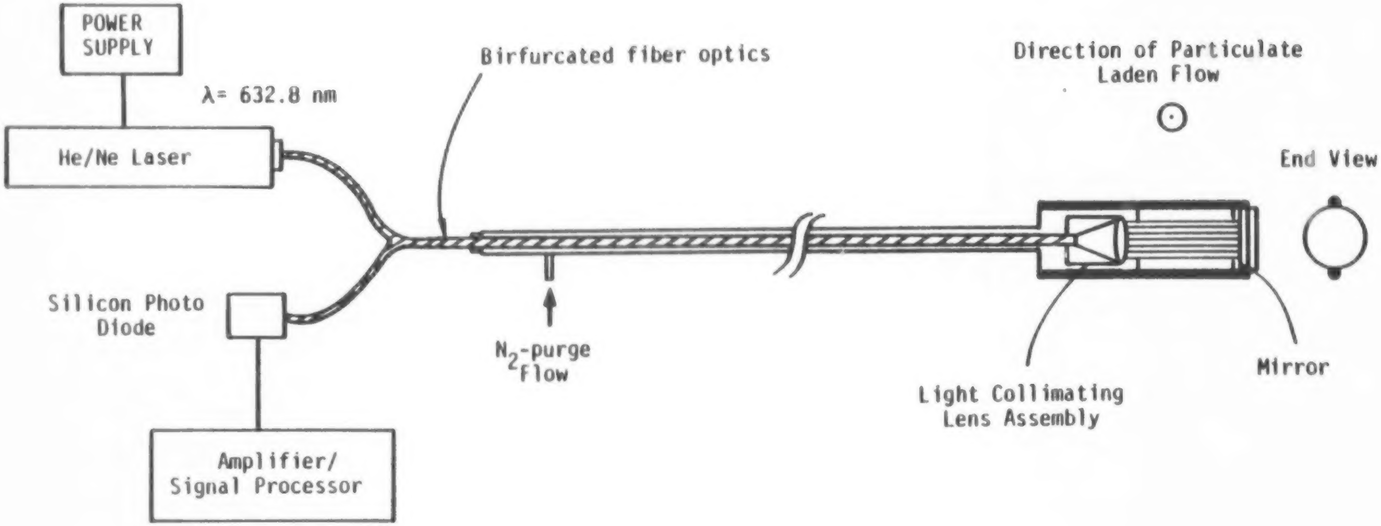
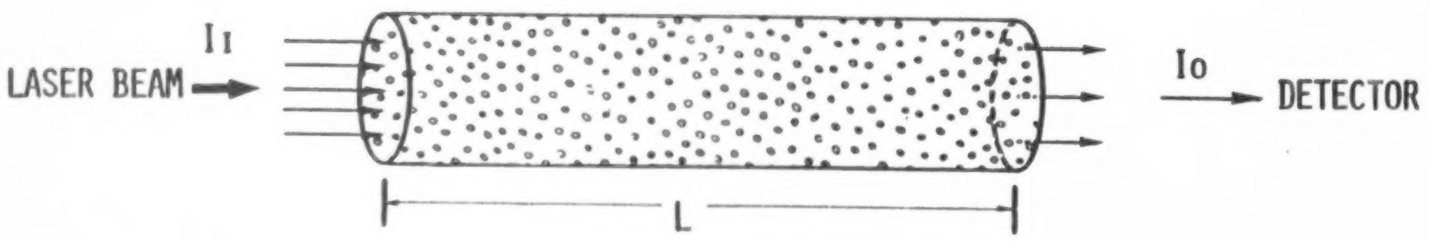

POWER SUPPLY
λ= 632.8 nm
He/Ne Laser
Silicon Photo Diode
Amplifier/ Signal Processor
Birfurcated fiber optics
N_2-purge Flow
Direction of Particulate Laden Flow
End View
Light Collimating Lens Assembly
Mirror

Figure 3-29. Fiber optics probe for laser extinction measurements.


I_I
LASER BEAM
L
Io
DETECTOR

$$I_O = I_I \, e^{-KL}$$

$$K = \frac{1}{L} \, \mathrm{LN}\left(\frac{I_I}{I_O}\right)$$

K = K (CONCENTRATION, PARTICLE SIZE)

Figure 3-30. Light extinction by particle cloud.

where k(r) is the extinction coefficient for particles of radius r and N(r) is the concentration of the particles of radius r in the sampling volume. For monodisperse particles, Eq. (3-14) can be simplifed to

$$K = k(r_o) \cdot N \tag{3-15}$$

where N is the particle concentration to be determined.

If the extinction cross sections for the particles is known, then the particle concentration can be obtained from

$$N = \frac{1}{k(r_o)L} \, \mathrm{Ln} \left(\frac{I_I}{I_0} \right) \tag{3-16}$$

However, the extinction cross sections of the limestone particles have to be known as a function of the particle size and rather involved deconvolution of integrals similar to those in equation (3-14) is required to determine the number densities as a function of particle size. This type of analysis was deemed to be beyond the scope of work intended in this study. Therefore, a more simplified approach was taken to determine the relative concentration levels instead of the distributions of particle number densities. This was done by determining the natural logarithm of the intensity (or signal) ratios which were then related to the relative concentration levels in the jet. Figure 3-31 shows the typical characteristics of the attentuation signal. Since intensity is linear with voltage (detector characteristics), the intensity ratio is related to the signals by,

$$\frac{I_0}{I_I} = \frac{V_p - V_o}{V_i - V_o} \tag{3-17}$$

However, due to some fouling of the optical parts, the baseline voltage V_f is usually somewhat less than V_i. This necessitated, calculation of the intensity ratio based on the following formula

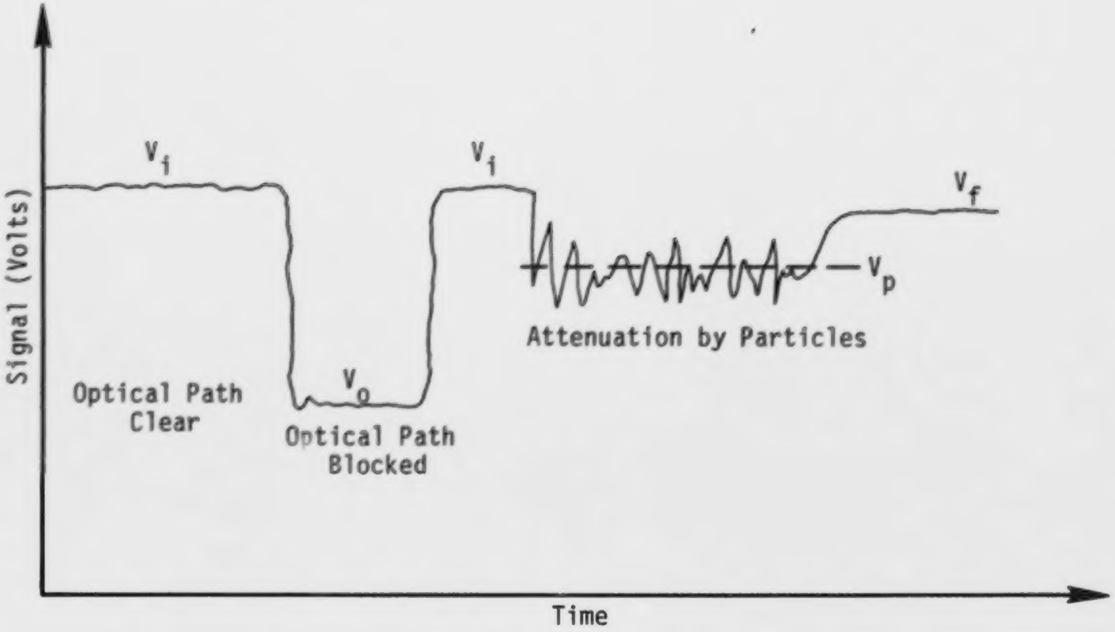


Figure 3-31. Characteristics of attenuation.

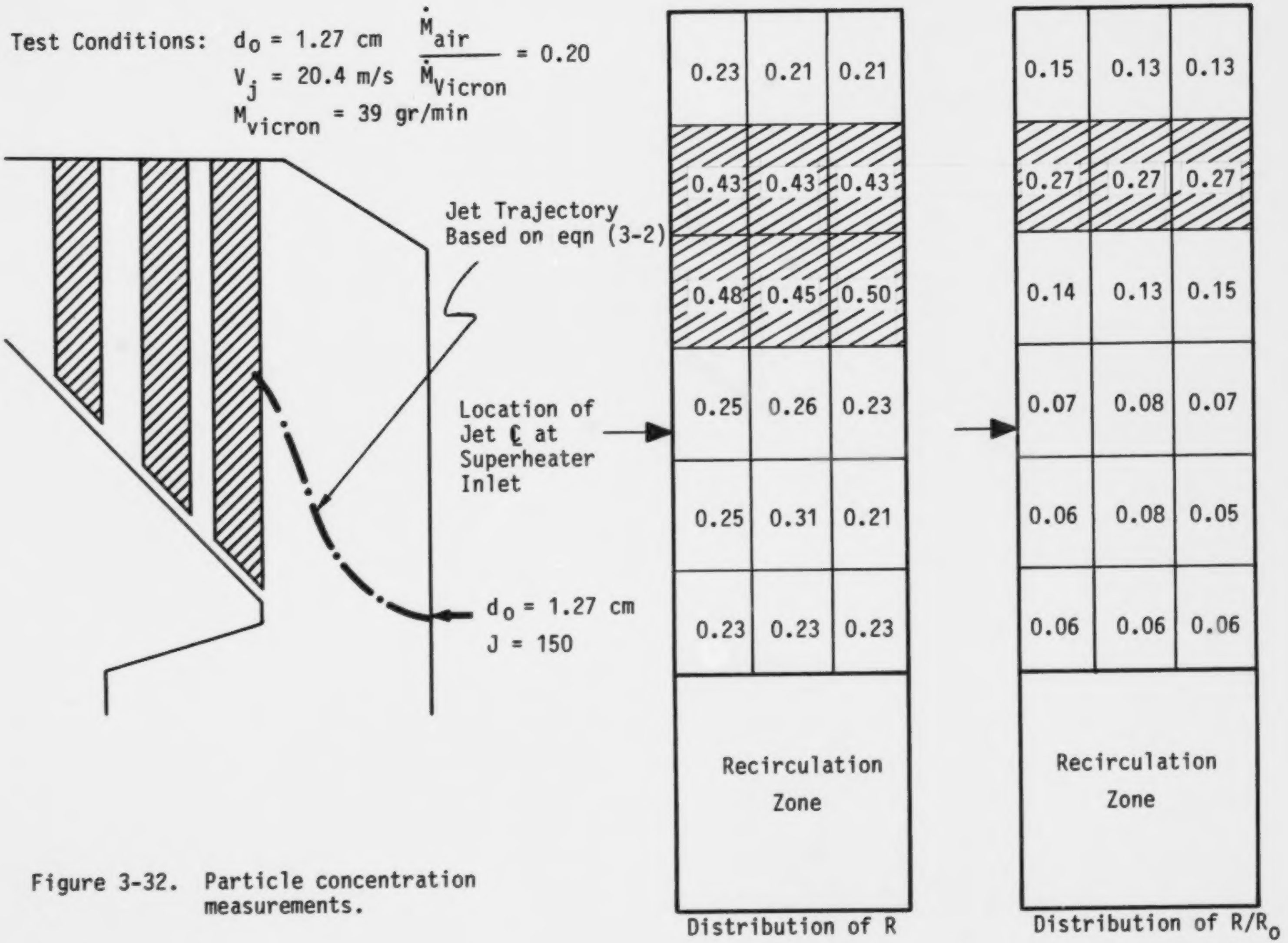
$$\frac{I_0}{I_I} = \frac{V_p - V_o}{\frac{V_i+V_f}{2} - V_o} \qquad (3\text{-}18)$$

The natural logarithms of the intensity ratios were taken to yield information on the relative concentration levels.

$$R = Ln\left(\frac{I_I}{I_0}\right) = Ln\left[\frac{\frac{V_i+V_f}{2} - V_o}{V_p - V_o}\right] \qquad (3\text{-}19)$$

Measurements were made in the flow cell with a 1.27 cm diameter jet at a momentum flux ratio of 150. Vicron 45-3 was fed with a single-screw feeder at a rate of 39 gr/min corresponding to a solid loading of 0.2. During these tests, some fluctuations in the feed rate were unavoidable. Figure 3-32 shows the distribution of R on the left-hand side. The numbers in this figure should be interpreted on a relative basis, 0.5 corresponding to the maximum particle concentration level. However, they represent the local relative particle concentrations. Based on this distribution, there was no appreciable variations across the width of the model and the maximum levels occurred somewhat above the calculated centerline location at the superheated inlet plane. This is expected since particles in the jet tend to be more concentrated in the wake of the jet. Because of the forementioned fluctuations in the feed rate, concentrations were measured at the jet exit several times during the test. The R distribution was normalized with the calculated values at the jet exit, R_0, which represented the measurements most closely in time. This distribution, shown on the right-hand side of Figure 3-32, indicated that the maximum concentrations occurred even higher in this cross section. The validity of this observation is questionable because of the rather ad-hoc way of correcting the R-distribution.

The smoke visualization and CH_4 tracer concentration measurements on the equivalent air jet indicated similar qualitative dispersion characteristics.


Test Conditions: $d_o = 1.27$ cm $\frac{\dot{M}_{air}}{\dot{M}_{Vicron}} = 0.20$
$V_j = 20.4$ m/s
$M_{vicron} = 39$ gr/min

Jet Trajectory
Based on eqn (3-2)
Location of
Jet ℄ at
Superheater
Inlet
$d_o = 1.27$ cm
J = 150
0.23 0.21 0.21
0.43 0.43 0.43
0.48 0.45 0.50
0.25 0.26 0.23
0.25 0.31 0.21
0.23 0.23 0.23
Recirculation
Zone
Distribution of R
0.15 0.13 0.13
0.27 0.27 0.27
0.14 0.13 0.15
0.07 0.08 0.07
0.06 0.08 0.05
0.06 0.06 0.06
Recirculation
Zone
Distribution of R/R_o

Figure 3-32. Particle concentration measurements.

3.3 Experiments in the Alternate Configuration Test Cell

Experiments discussed in the previous section concerned the dispersion characteristics of jets injected into the flow field of a particular boiler upper furnace geometry. Although many features of the flow field are common in wall-fired boilers, different upper furnace designs are employed by various boiler manufacturers. Figure 3-33 shows the typical upper furnace configurations for wall and tangentially fired boilers. Table 3-4 identifies these configurations with the type, boiler manufacturer and the typical unit size. Because of these significant variations in upper furnace geometries, an upper furnace test model was built to study the effects of upper furnace geometry and jet location with respect to the nose constriction in a systematic way. In addition, two jets in uniform cross flow were studied in detail to obtain information on the entrainment in the near field of these jets.

Figure 3-34 shows the model used for these studies. It consisted of a 0.61 meter square cross section vertical pass constructed from 6.3 mm thick acrylic plates. At the top, flow could exit horizontally from the 90° bend while simulating boiler type flows or it could exit the model through the top vertically for studies of jets in uniform cross flow.

Three series of tests were conducted in this alternate configuration test model. First, the effects of the main furnace flow characteristics on the jet trajectories were investigated by screening experiments with smoke injection through the simulated sorbent jets. Second, the various means of scaling non-isothermal jets were studied. Dispersion measurements were conducted for two test cases and compared with combustor dispersion patterns from data obtained in pilot scale dispersion furnace tests. Third, two jets in uniform cross-flow were mapped in detail for velocity and tracer concentration to obtain data needed for jet model validation discussed in the next section. The next subsection discusses the effects of furnace geometry on the jet trajectories.

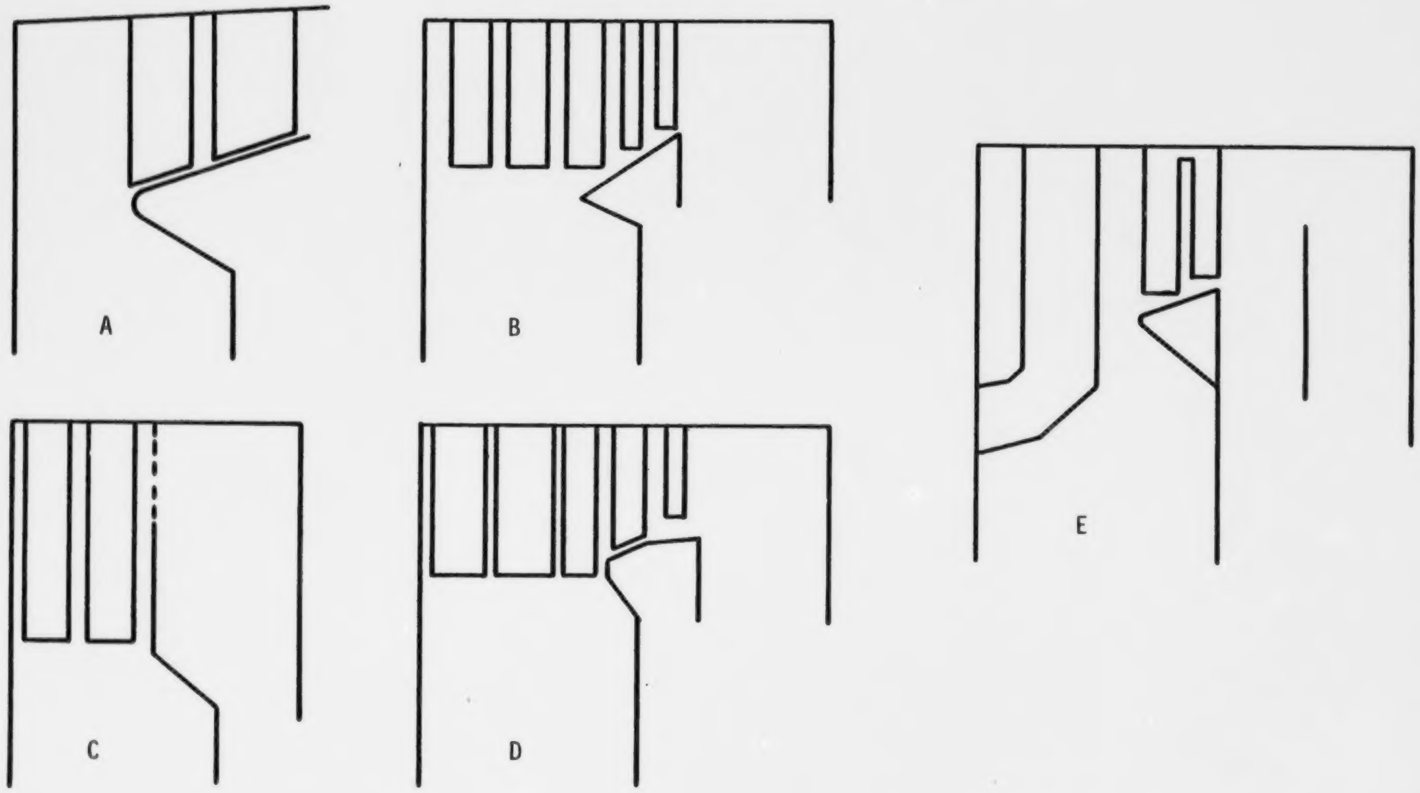
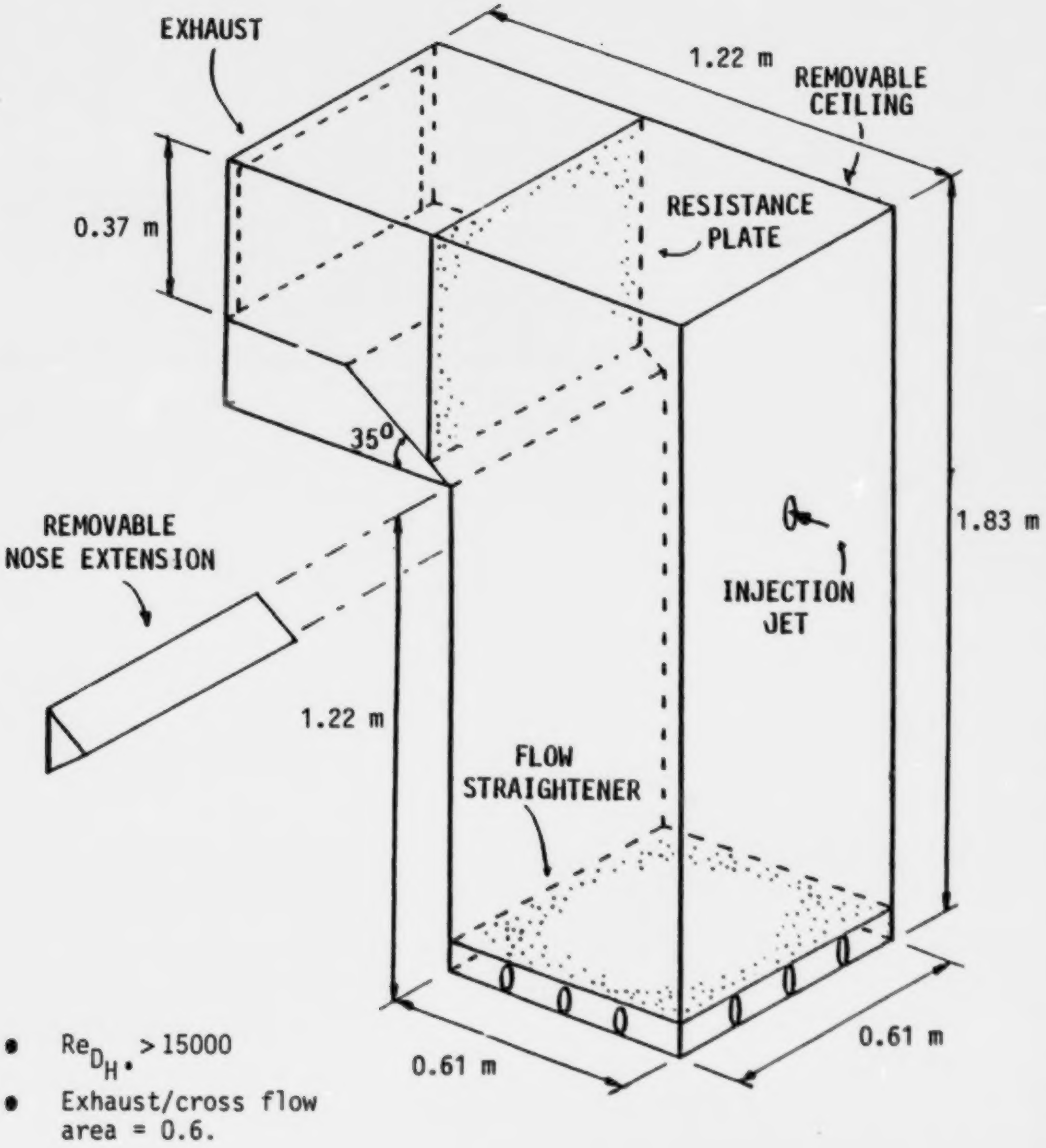


Figure 3-33. Upper furnace configurations.

TABLE 3-4. BOILER UPPER FURNACE CONFIGURATIONS

Configuration	Firing Conf.	Boiler Manufacturer	Unit Size, MW_e
A	Wall-Fired	Foster-Wheeler	50-200
	Wall-Fired	Babcock & Wilcox	50-500
	T-Fired	Combustion Engineering	50-200
	Wall-Fired	Riley-Stoker	50-200
B	Wall-Fired	Foster-Wheeler	500-800
	Wall-Fired	Babcock & Wilcox	500-800
C	Wall-Fired	Riley-Stoker	200-500
D	T-Fired	Combustion Engineering	200-800
E	Wall-Fired Divided Back Pass	Foster-Wheeler	500-800


EXHAUST
1.22 m
REMOVABLE CEILING
0.37 m
RESISTANCE PLATE
35°
REMOVABLE NOSE EXTENSION
1.83 m
INJECTION JET
1.22 m
FLOW STRAIGHTENER
0.61 m
0.61 m

- $Re_{D_H}. > 15000$
- Exhaust/cross flow area = 0.6.

Figure 3-34. Alternate configurations flow channel.

3.3.1 Screening Studies of Jet Injection

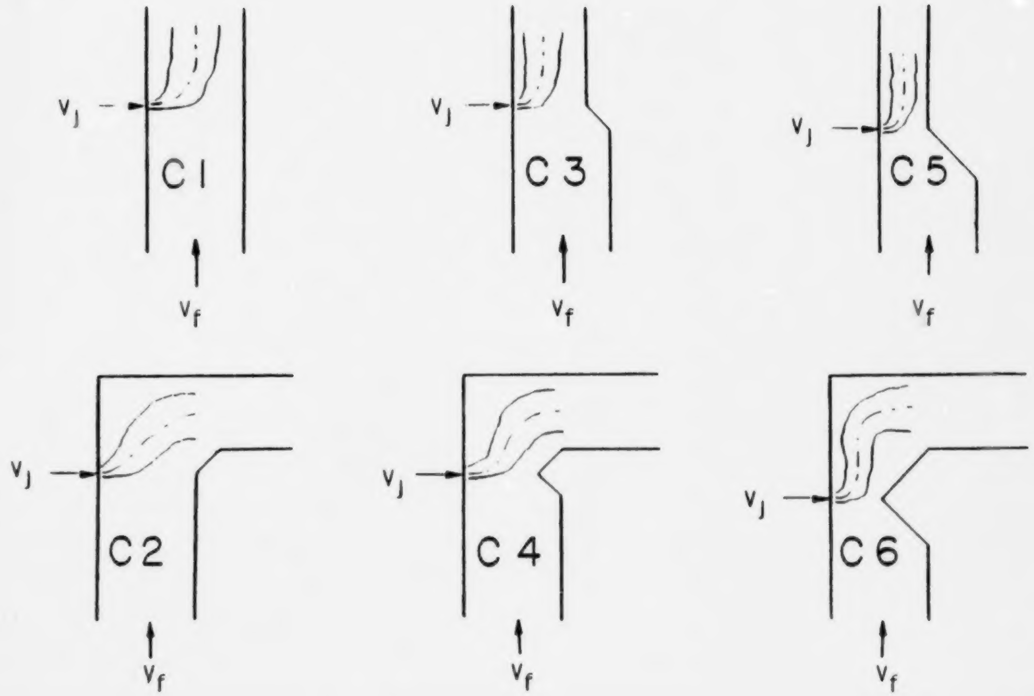
The test configurations used during these studies are shown in Figure 3-35. These configurations were selected to systematically study the effects of nose constriction and turning flow on the trajectories and the spread of injection jets. The test matrix for the screening tests is shown in Table 3-5. This matrix allowed to study:

- effects of the main flow field characteristics on jet trajectories.
- effect of jet diameter and momentum flux ratio on jet trajectory
- effect of duct depth on jet trajectories.

The nomenclature associated with the injection configurations are shown in Figure 3-36. The selection of test parameters and the test results are discussed in the following subsection.

3.3.1.1 Screening Test Results

The effects of main flow field characteristics were first investigated in a straight duct with varying degrees of contraction simulating the nose geometry. In these experiments, the main flow did not experience a 90° turn as occurs in the boiler upper furnace flows. The intention was to study the contraction and turning effects separately. Figure 3-37 shows the sketches of jet smoke traces for the three contraction ratios, 0, 25 percent and 50 percent, the latter two representing typical contraction ratios for wall-fired boilers. A single 0.89 cm diameter jet was injected in the middle span of the front wall at the elevation of the contraction. Figure 3-37a shows the jet trajectory at momentum flux ratios of 50, 100 and 150 with 50 percent contraction. It can be seen that the variation of the momentum flux ratio provided an effective control of the jet penetration into the main flow. The momentum flux ratios for 25 percent contraction were calculated from equation (3-2) to achieve the same relative jet penetration into the main flow, compared to the 50 percent contraction case.


V_j
C1
V_f
V_j
C3
V_f
V_j
C5
V_f
V_j
C2
V_f
V_j
C4
V_f
V_j
C6
V_f

Test Configurations

C1: Straight Duct

C2: 90° Turning Duct

C3: 25% Reduction
Straight Duct

C4: 25% Reduction
90° Turning Duct

C5: 50% Reduction
Straight Duct

C6: 50% Reduction
90° Turning Duct

Figure 3-35. Test configurations.

TABLE 3-5. SCREENING STUDY TEST MATRIX

Configuration (Uniform Velocity)	Injection Location	n	d_o, cm	H/d_j	J
C1: Straight Duct	0	1	0.89	68.2	150 346 965
	0	1	1.57	38.9	65
C2: Turning Duct	+E/4	1	0.89	68.2	150 346 965
	-E/4	1	0.89	68.2	150 346 965
C3: 25% Reduction Straight Duct	0	1	0.89	51.1	150 257 431
	0	1	1.28	35.6	88 150 252
C4: 25% Reduction Turning Flow	+E/4	1	0.89	51.1	150 257 431
	0	1	0.89	51.1	150
	-E/4	1	0.352	51.1	150 257 431
C5: 50% Reduction Straight Duct	0	1	0.89	34.1	50 100 150
C6: 50% Reduction Turning Flow	+E/4	1	0.89	34.1	50 100 150
	-E/4	1	0.89	34.1	50 100 150

n = Number of jets
d_o = Nozzle diameter
H = Duct depth at point of injection (front to back)
E = Model depth (= 0.61 m)

$$J = \frac{\rho_j V_j^2}{\rho_f V_f^2}$$

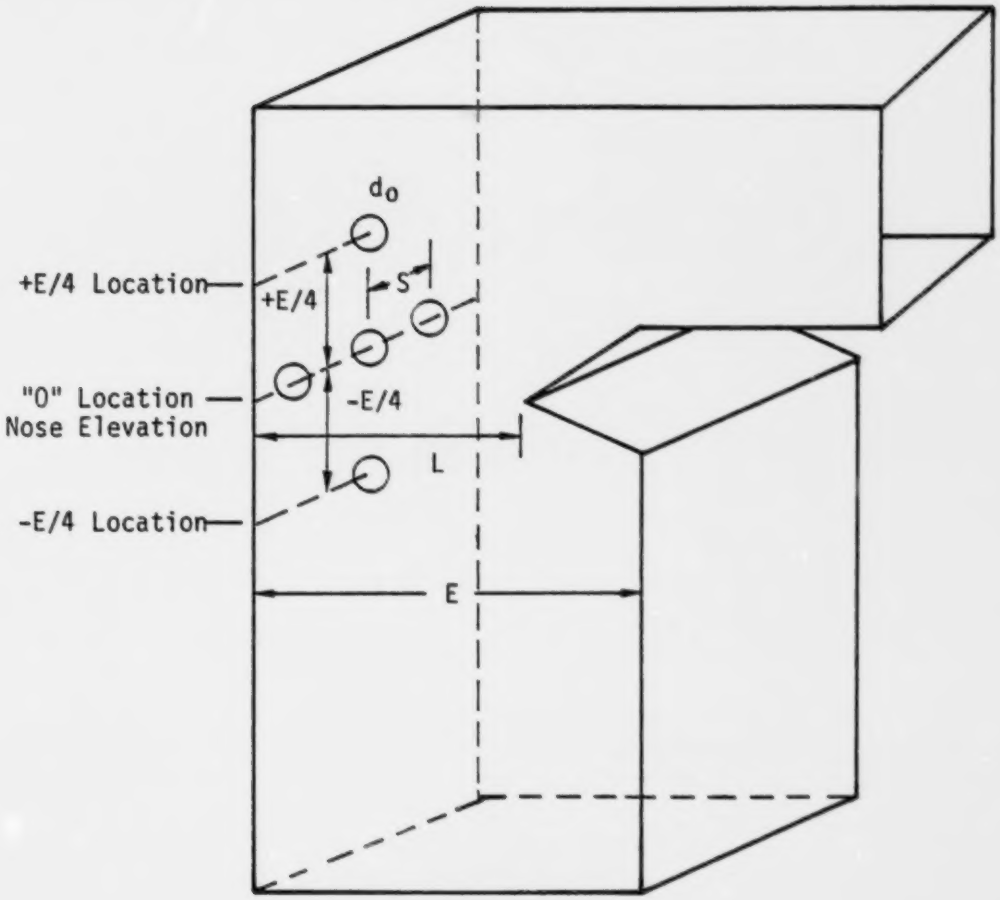

d_o
+E/4 Location
+E/4
S
"0" Location
Nose Elevation
-E/4
L
-E/4 Location
E

Figure 3-36. Injection location nomenclature.

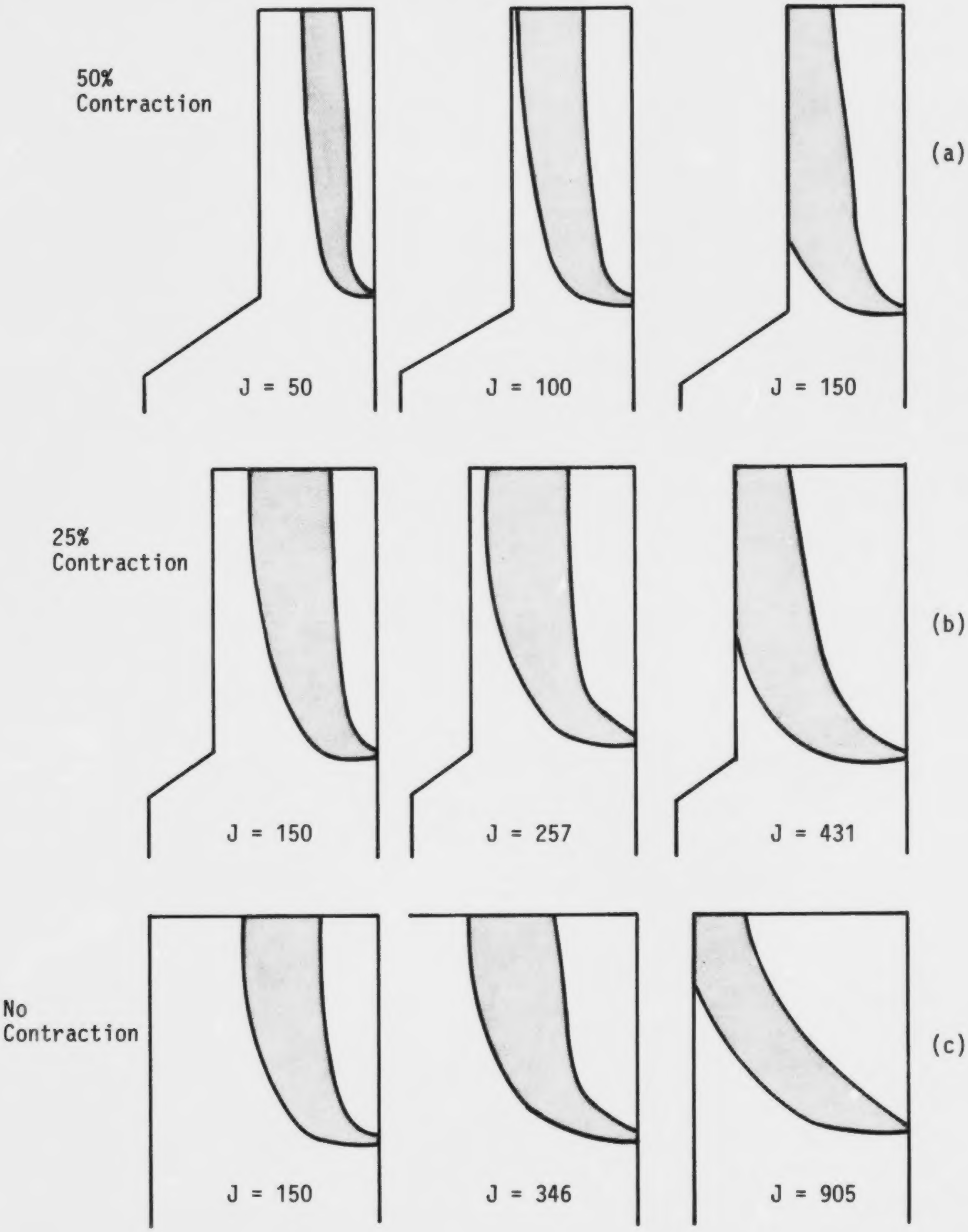
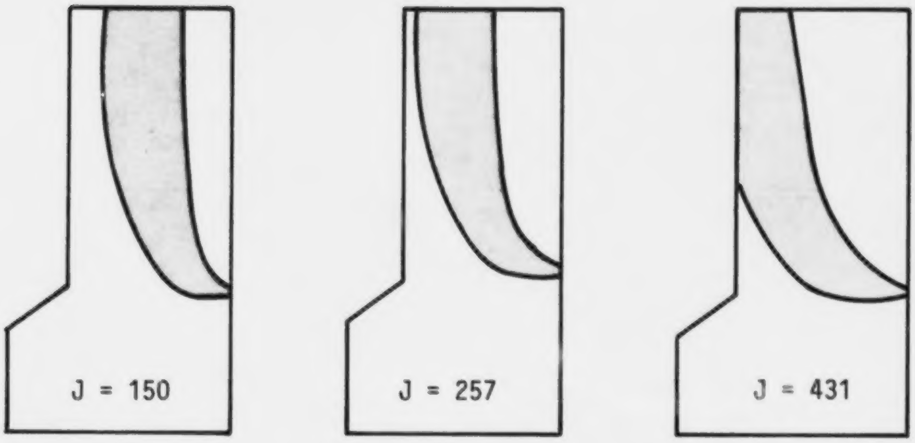

50%
Contraction
J = 50
J = 100
J = 150
(a)
25%
Contraction
J = 150
J = 257
J = 431
(b)
No
Contraction
J = 150
J = 346
J = 905
(c)

Figure 3-37. Effect of jet momentum and upper furnace geometry on jet trajectories for a single 0.89 cm. diameter jet injected at the front wall.

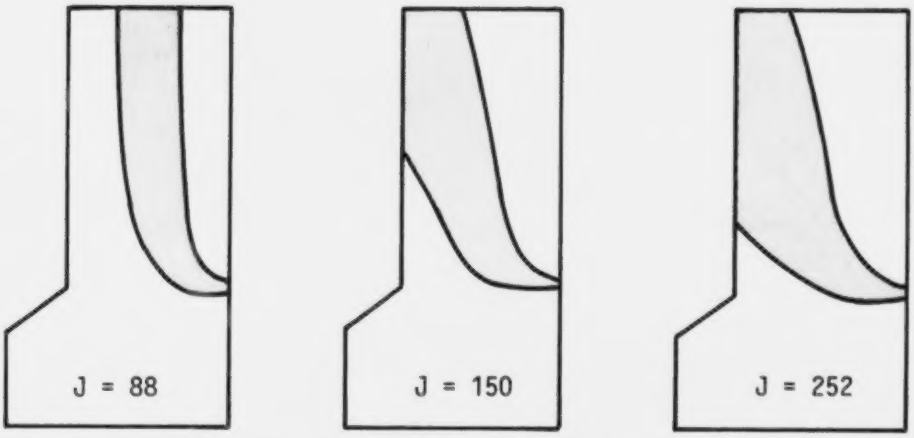
Figure 3-37b shows the jet trajectories at the adjusted momentum flux ratios for 25 percent contraction. Jet penetrations relative to the depth of the upper contracted section are similar for the two momentum flux ratios; J = 257 and J = 431. This similarity suggests that the empirical trajectory equation used to scale-up the momentum ratios does give a reasonable estimate of the jet trajectories, even in the non-uniform flow field. The case with J = 150 compares with the same momentum ratio for the 50 percent contraction, revealing the effect of the flow contraction. However, it should be pointed out that the jet velocity for 50 percent contraction case was higher than that for 25 percent contraction to match the momentum flux ratio. The behavior of the jet in a uniform flow is depicted in Figure 3-37c.

Figure 3-38 shows the effect of the jet diameter on the penetration for 25 percent contracted duct. Comparison of 0.89 cm diameter jet with the 1.28 cm diameter jet at J = 150, indicates that larger diameter jet penetrated into the cross flow further than the small jet as predicted by the jet trajectory equation. The low, medium and high momentum flux ratios of the large and small diameter jets were selected to yield similar jet trajectories based upon the empirical jet trajectory equation. Comparison of the low momentum flux ratio tests showed good agreement between the two jet trajectories. However, as the jet momentum flux was increased, the larger jet appeared to penetrate slightly farther. This result is most likely due to the nonlinear dependence of entrainment on the jet momentum flux ratio.

Figure 3-39 shows the effect of the turning flow on the jet trajectories. In all cases, the initial bending of the jet by the cross flow is followed by the turning of the jet towards the entrance of the superheater plates. The initial trajectories of these jets can be predicted by the empirical trajectory equation (3-2) reasonably well as shown by dashed-dotted lines representing predicted centerline trajectories. The predicted trajectories gradually deviate from the smoke traces because of the turning of the jet in the main flow field. The effect of increasing the contraction ratios is to suppress the penetration of the jet and increase its bending due to the higher velocity region near the nose. This is also shown in Figure

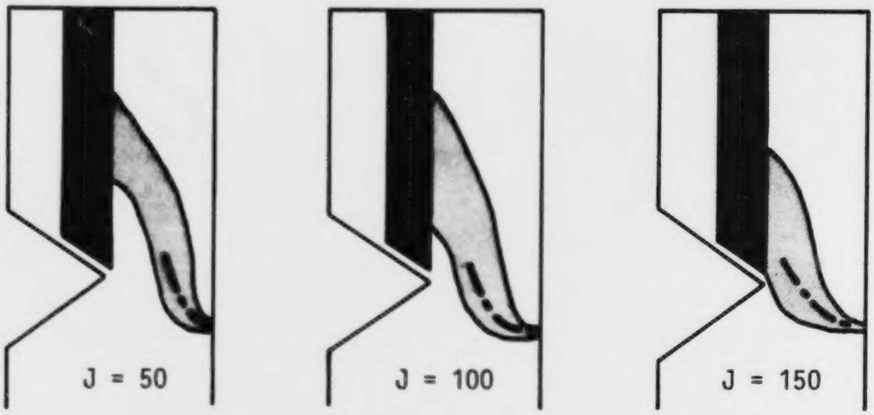

J = 150
J = 257
J = 431

Single 0.89 cm. diameter jet injected at nose.

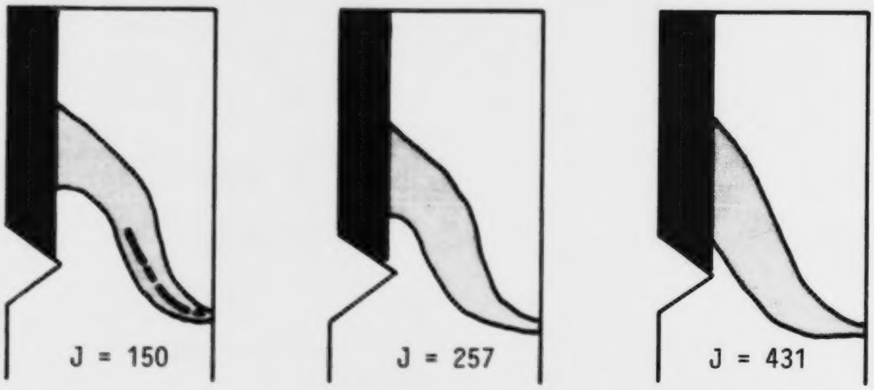

J = 88
J = 150
J = 252

Single 1.28 cm. diameter jet injected at nose

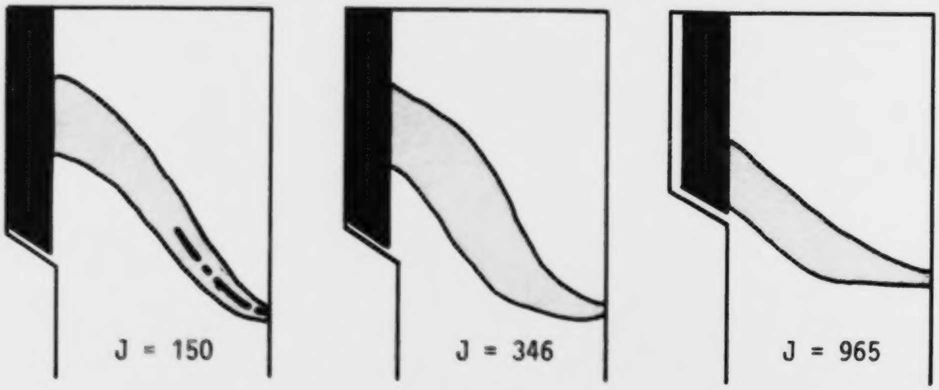
Figure 3-38. Effects of jet diameter and momentum on jet trajectories in a straight 25% contracting duct.


J = 50
J = 100
J = 150

50% Contraction


J = 150
J = 257
J = 431

25% Contraction


J = 150
J = 346
J = 965

No Contraction

Figure 3-39. Effect of turning flow on the trajectory of a single 0.89 cm diameter jet at different momentum flux ratios.

3-40a for a 0.89 cm diameter jet at a momentum flux ratio of 150.* The initial jet trajectories are again predicted reasonably well from equation (3-2).

Finally, Figure 3-40 shows the effect of changing jet elevation on the front wall with respect to the nose elevation. In the same flow field (50 percent contraction), the location of the jet on the front wall determines its location at the entrance of the superheater section. When injected below the nose, a 0.89 cm diameter jet at J = 50 penetrates into the recirculation zone. This can be avoided either by reducing the jet momentum or by moving the jet to a higher elevation. At injection elevations above the nose, the jets begin to experience reduced effects of cross flow since the main flow makes a turn toward the superheater plane. In such cases, the penetration is dominated to a lesser extent by the momentum flux ratios.

So far, the effects of the main flow characteristics, and jet injection parameters on the jet trajectories and dispersion were qualitatively studied in isothermal models. The next subsection concerns the scaling procedures of jet parameters to provide a realistic simulation of sorbent jets injected into a hot furnace environment in an isothermal study.

3.3.2 Studies on Isothermal Scaling of Jets and Comparisons With Combustion Test Results

The key assumption in conducting isothermal jet injection studies designed to simulate injection scenarios in a combustor is that the proper scaling criteria ensure the similarity of mixing characteristics and dispersion patterns. The parameters influencing the penetration and the trajectory of jets was established in the preceding sections. These are the jet to cross-flow momentum flux ratio and the jet diameter influencing both jet trajectories and entrainment.

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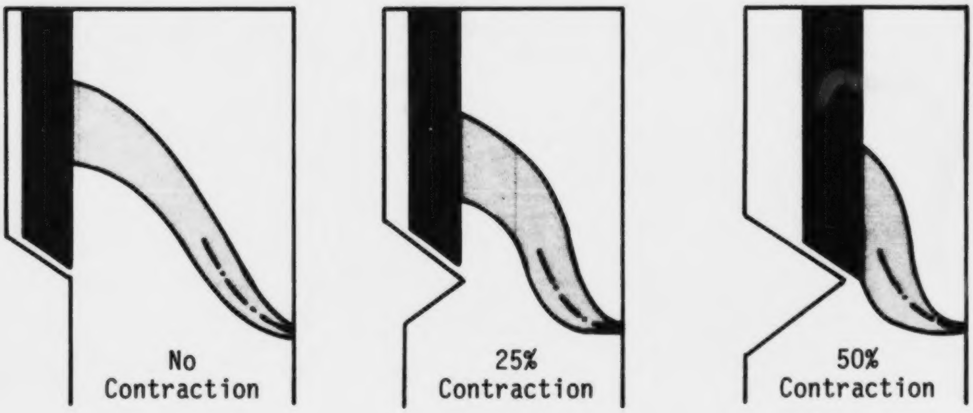
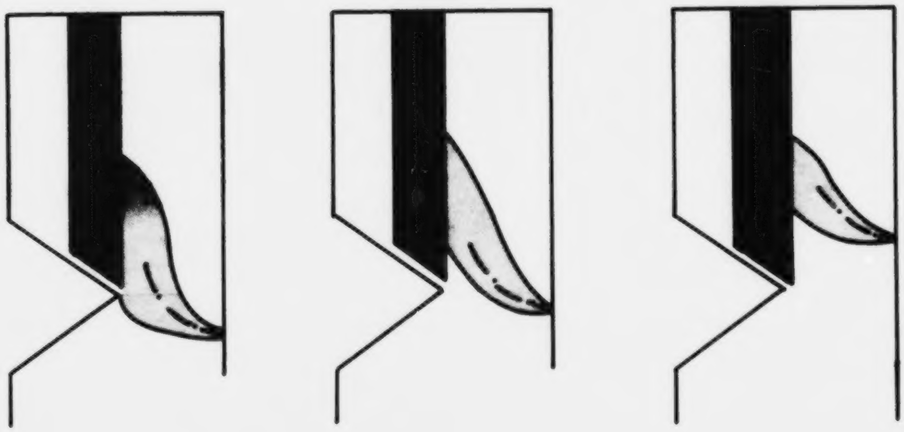
* Jet momentum flux ratios were calculated based on the plug flow conditions at the nose plane in all cases for simplicity.


No Contraction
25% Contraction
50% Contraction

a) Effect of nose contraction on the jet trajectory



b) Effect of jet location on jet trajectory

Figure 3-40. Effects of upper furnace geometry and jet location on the trajectory of a single 0.89 cm diameter jet at a momentum flux ratio of 150.

3.3.2.1 Injection Jet Scaling

In mathematical modeling studies of jets in cross-flow described in Section 4.0, it was determined that a cold jet entering the hot combustor environment would entrain at a lower rate than its isothermal counterpart, the ratio of entrainment rates being related to the ratio of the ambient and the jet fluid densities (similar to the free jet entrainment). This effect can be most clearly explained for a free turbulent jet under isothermal and non-isothermal conditions. The entrainment of a round turbulent, free jet (17) is given by:

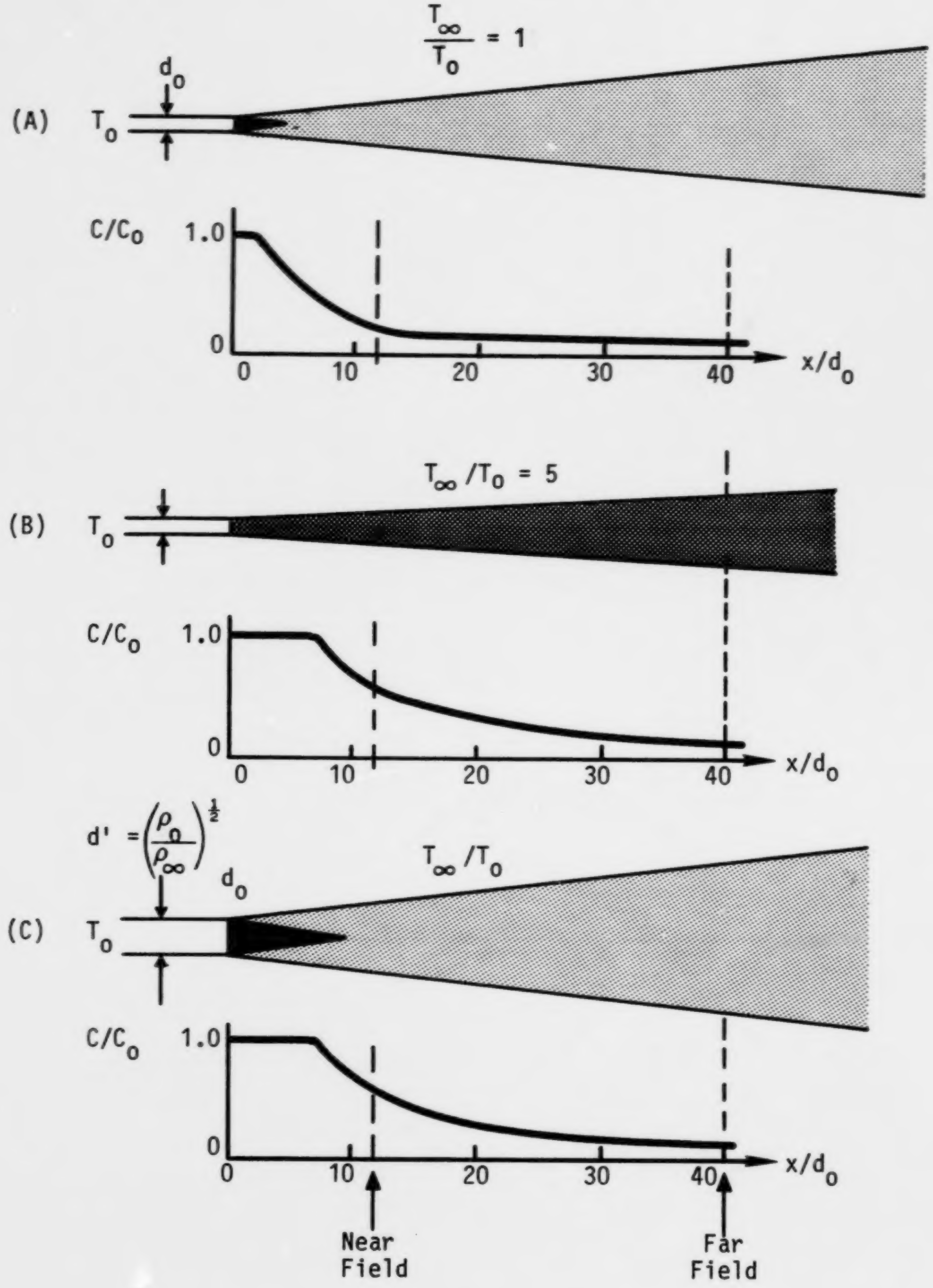
$$\frac{\dot{M}_x}{\dot{M}_o} = 0.32 \left(\frac{\rho_\infty}{\rho_o}\right)^{1/2} \frac{x}{d_o} \tag{3-20}$$

where $\dot{M}_o$ is the jet mass flux at the origin, $\dot{M}_x$ is the mass flux at a downstream location, x; ρ_∞ and ρ_o are the ambient and jet density at the jet origin respectively. The rates of the jet fluid dilution along the jets were calculated for an isothermal jet ($T_\infty/T_o = 1.0$) and a non-isothermal jet ($T_\infty/T_o = 5.0$) based on the above equation (3-20). The results are shown in Figure 3-41 as Cases A and B for isothermal and non-isothermal cases respectively. When compared with respect to their spread and dilution, the cold jet (Case B) spreads at a slower rate, with a corresponding lower rate of dilution.

The differences in the dilution rates are most prominent in the first 10 to 15 jet diameters downstream, but they become almost indistinguishable for the isothermal and the non-isothermal jets at large downstream locations (far field).

One method to account for the differences of the dilution and spread in the near field is by modifying the jet diameter by

$$d' = \left(\frac{\rho_o}{\rho_\infty}\right)^{1/2} d_o \tag{3-21}$$



$\frac{T_\infty}{T_o} = 1$
d_o
(A)
T_o
C/C_o
1.0
0
0
10
20
30
40
x/d_o
$T_\infty/T_o = 5$
(B)
T_o
C/C_o
1.0
0
0
10
20
30
40
x/d_o
$d' = \left(\frac{\rho_o}{\rho_\infty}\right)^{\frac{1}{2}}$
d_o
T_∞/T_o
(C)
T_o
C/C_o
1.0
0
0
10
20
30
40
x/d_o
Near Field
Far Field

Figure 3-41. Jet scaling techniques.

such that the dilution rates downstream become similar. This approach is similar to Thring-Newby scaling criteria (18) which was developed for isothermal scaling of burners by accounting for the combustion front. Comparisons of Cases B and C in Figure 3-41 indicate that this approach gives a better match in terms of jet entrainment and far field jet spread. However, the near field jet spread is overestimated.

In order to evaluate the effect of jet diameter scaling, CH_4 tracer concentration measurements were made along the jet trajectory for two jets. A 2.54 cm diameter jet with a momentum flux ratio of 15.4 was studied in the alternate configurations model with 50 percent contracted, 90^0 turning flow. The jet diameter was modified for a density ratio of 5.3 to obtain a 5.84 cm diameter jet. The jet trajectory was kept similar to that of the 2.54 cm jet by adjusting the jet momentum flux ratio to 4.6.

Tracer concentration measurements were made along the jet centerline trajectory in the near field. Figure 3-42 shows that the relative dilution rates for both jets in non-dimensional form are similar. This is expected since both jets are isothermal (jet fluid density = cross-flow stream density). However, the variation of the normalized tracer concentration with actual distance along the jet is different for these two cases as shown in Figure 3-43. The 5.84 cm diameter isothermal jet has a lower rate of dilution than the 2.54 cm diameter isothermal jet. Since an isothermal jet entrains at a rate which is inversely proportional to the jet diameter, the effect of density can be imbedded into the jet diameter to simulate a non-isothermal situation. For example, a 2.54 cm diameter dense jet into a light environment with a density ratio ρ_0/ρ_∞ = 5.3 would give a dilution rate similar to the 5.84 cm diameter isothermal jet. Therefore, square-root-of-density scaling of the jet diameters (similar to Thring-Newby scaling (18) correctly accounts for the non-isothermal effects, although the potential core of the expanded jet is longer, and the initial jet spread is not exactly simulated. However, in the far field, the differences are indistinguishable and geometric scaling can be used for far field evaluations. Therefore, for the measurements of tracer concentration at the superheater inlet plane, geometric scaling of jet diameters is equally valid. This is also

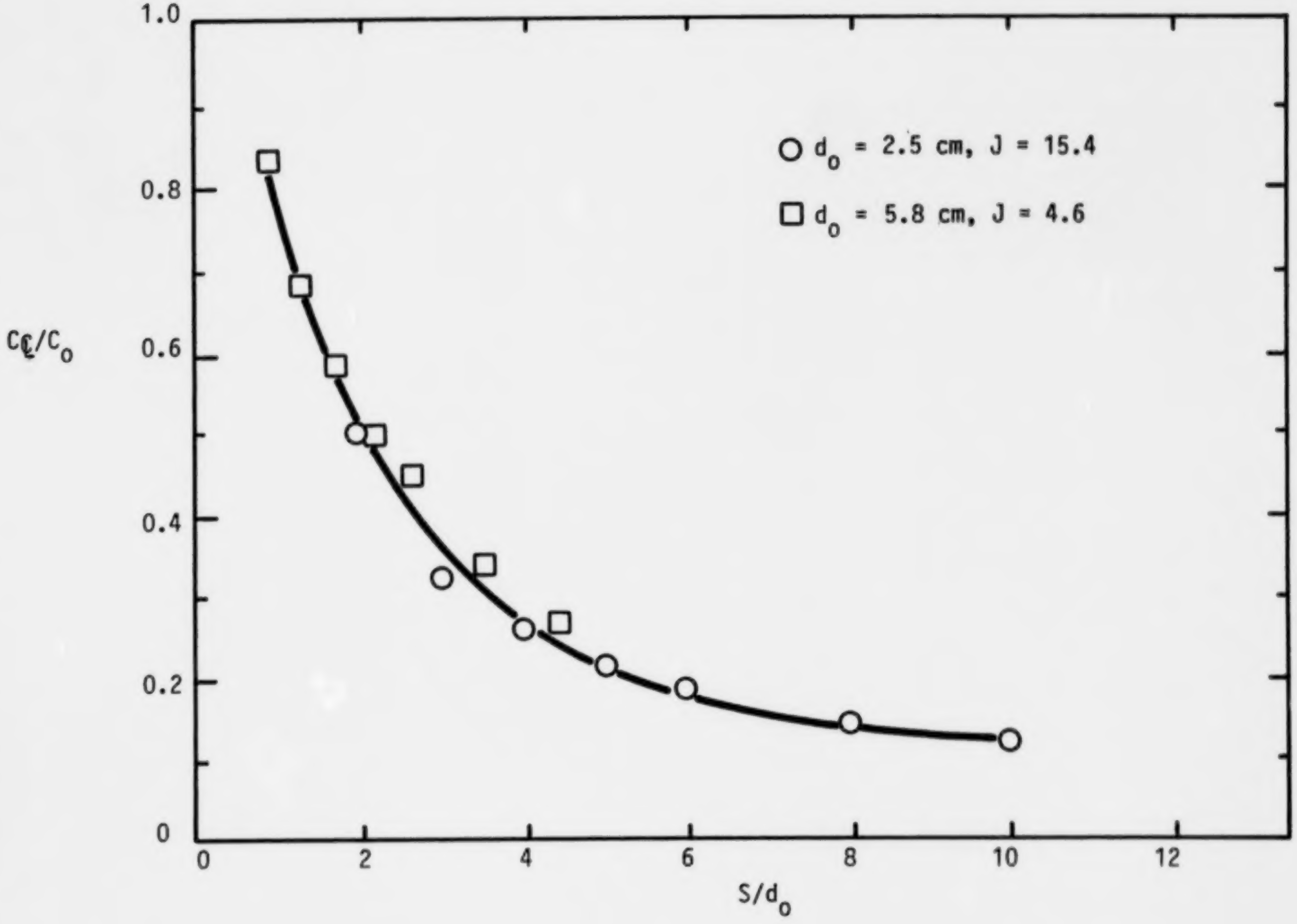


Figure 3-42. Non-dimensionalized tracer concentration variation along the jet centerline trajectory normalized with jet diameter.
$C_{\text{℄}}$: centerline tracer concentration, C_o: tracer concentration at nozzle exit, S: Distance from nozzle exit along jet centerline, d_o: jet diameter.

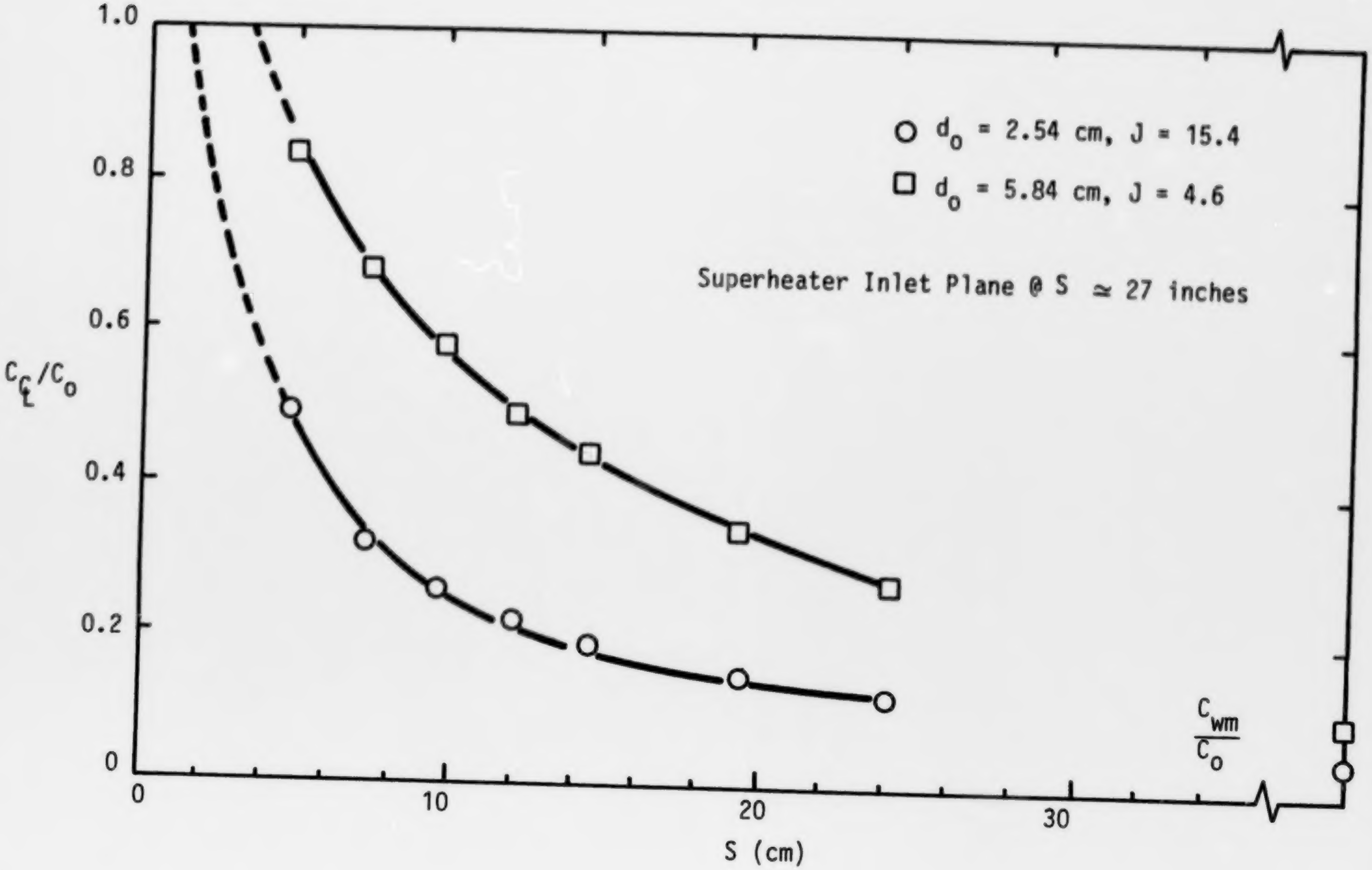


Figure 3-43. Variation of normalized tracer concentration along the jet centerline trajectory. $C_{℄}$: Centerline tracer concentration, C_o: Tracer concentration at nozzle exit, S: Distance from nozzle exit along jet centerline.

demonstrated by the similarity of the tracer dispersion profiles measured at the superheater inlet for the 2.54 cm and 5.84 cm diameter jets shown in Figure 3-44. The relative spread and magnitudes of the tracer concentrations for both jets indicate that the geometric and Thring-Newby scaling give similar results in the region far downstream of the injection point.

Comparison of Dispersion Patterns from Isothermal and Combustion Tests

In order to be able to use results from isothermal test to obtain information for the corresponding combustion conditions, the validity of isothermal modeling approach needs to be confirmed. During the combustion tests, described in Section 5.0, detailed tracer concentration measurements were made for a 5.08 cm diameter jet located at the nose elevation in the middle span of the front wall. A small amount of SO_2 was introduced into the jet and steady state concentrations were measured at the superheater inlet plane. The normalized (with respect to well-mixed exhaust concentration) tracer concentrations from this study are compared with the corresponding Thring-Newby scaled isothermal jet in Figure 3-45. The results indicate a slightly larger spread of the jet in the combustion case. Turbulent Schmidt numbers

$$Sc = \frac{\nu}{\mathscr{D}}$$

where ν is the kinematic viscosity and
$\mathscr{D}$ is the mass diffusion coefficient

for the isothermal and the combustion tests were around unity so that the differences in diffusivity could not account for the larger spread in the combustion case. The location of the highest tracer concentration was somewhat lower for the combustion test. This is possibly due to some differences in the flow patterns and jet penetrations in isothermal and combustion tests. However, isothermal simulation gives a reasonable description of the combustion case.

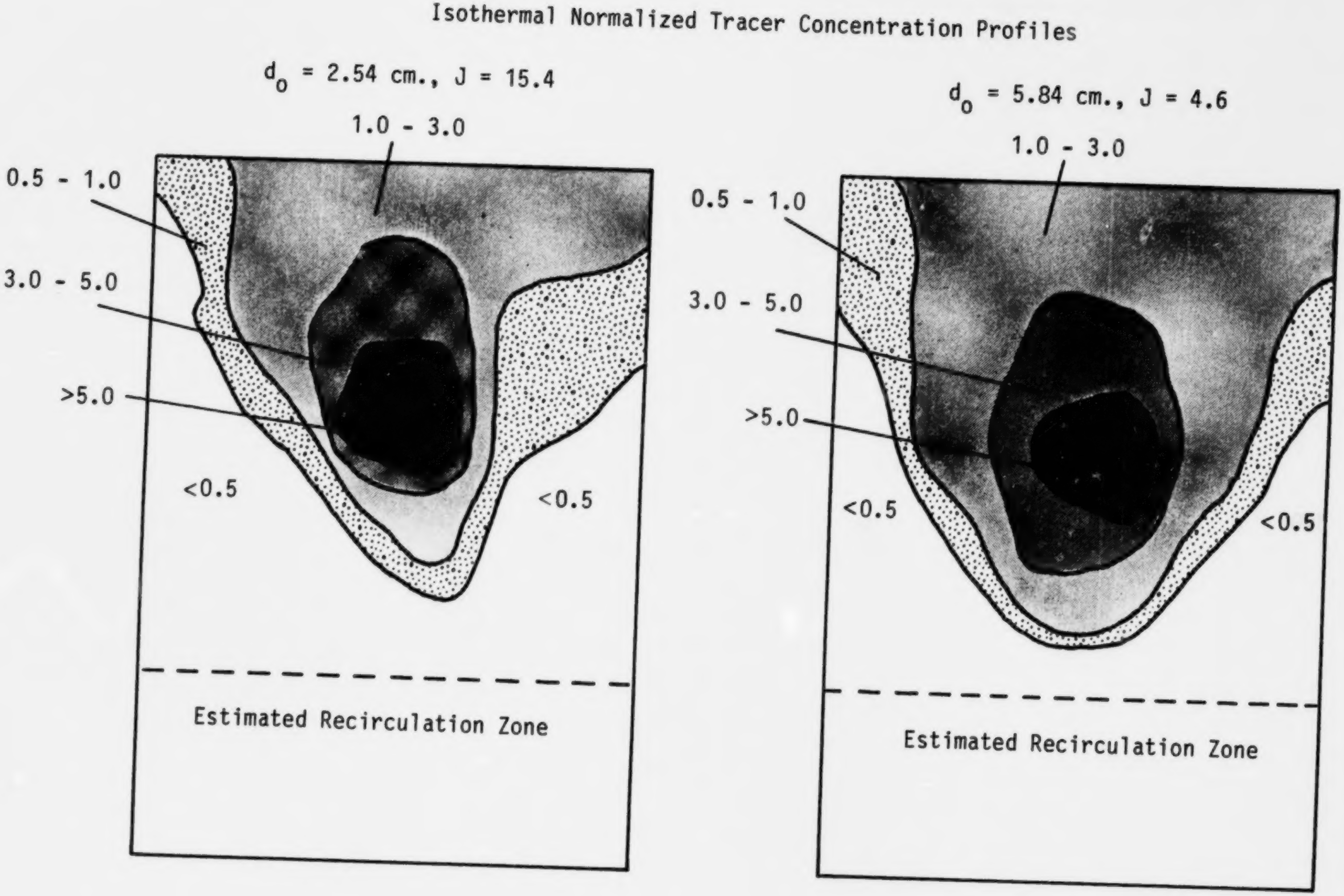


Figure 3-44. Normalized tracer concentration maps at the superheater entrance plane under isothermal conditions with 2.54 and 5.84 cm. diameter jets.

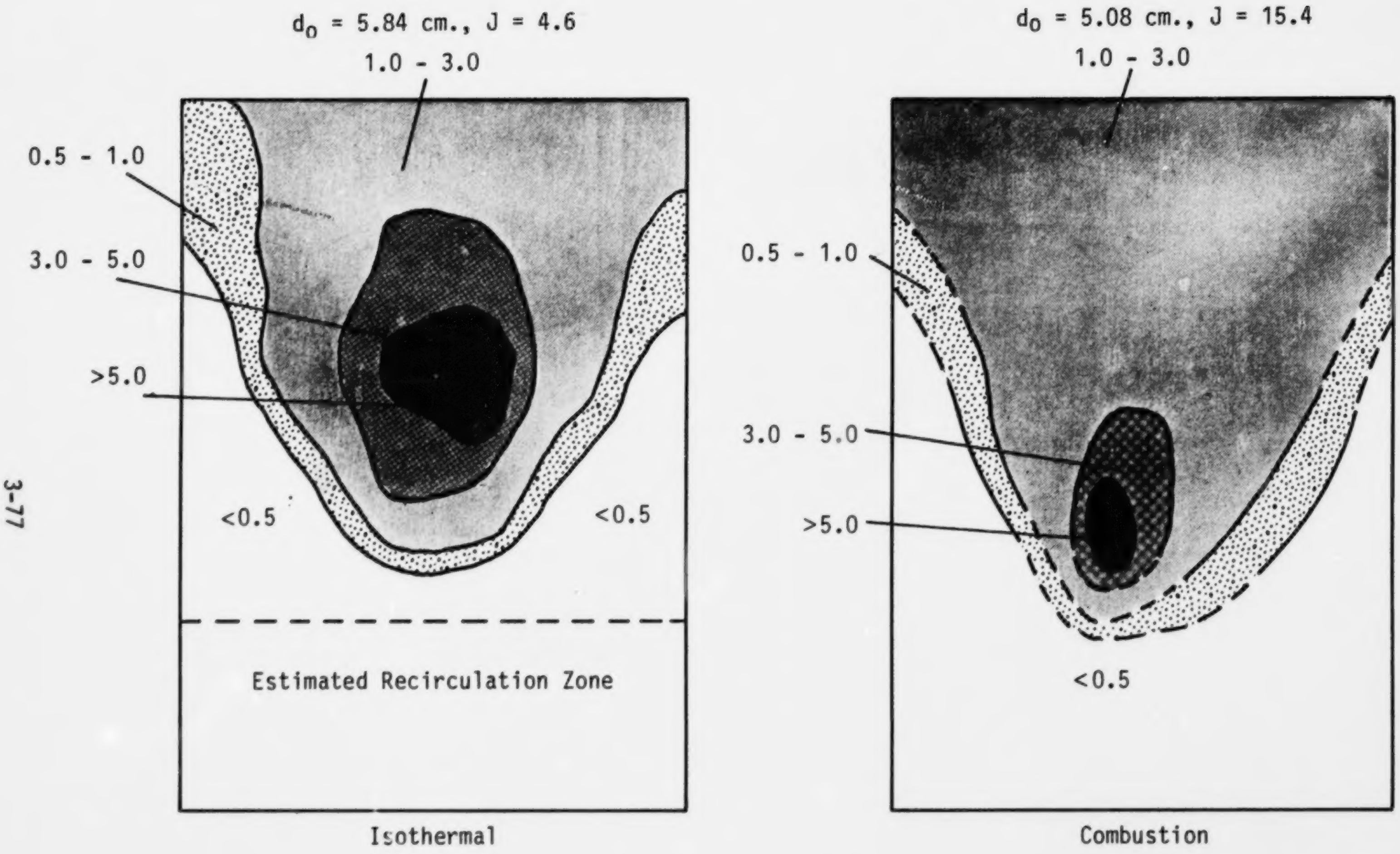


Figure 3-45. Comparison of isothermal and combustion dispersion patterns for a single jet injected at the nose level.

3.3.3 Detailed Jet Characterization

Review of the literature on jets in cross-flow revealed that the information on the entrainment rates of jets in cross-flow was very scarce and inconsistent. Since the entrainment rate in the early part of the jet determines the particle heating rates and peak particle temperatures, some effort was spent in studying the entrainment characteristics. Inherent difficulties exist in making point measurements of velocity and temperature (to obtain density) across the jet cross sections and integrate them to find the total mass flow rate in a turbulent free jet due to intermittency and large scale entrainment. These difficulties become greater for a jet in cross flow. In the case of a free turbulent jet, such difficulties led investigators Ricou & Spalding (17) to consider a different technique which is based on a mass conservation method. Such a method could not be used for a jet in cross-flow due to the presence of the cross-flow stream. Therefore, the approach taken here was to develop a simple integral model of jet injection based on a prescribed entrainment model and conservation equations for momentum and energy as described in Section 4.0. In order to calibrate this model, two jets were selected for detailed tracer and velocity mapping in the region from the nozzle exit down to 7 diameters downstream along the jet trajectory centerline as shown in Figure 3-46. The measured profiles of velocity and tracer concentration were analyzed to produce the parameters predicted by the model. The two jets systems studied were:

- a single 1.27 cm diameter jet at a momentum flux ratio, J, of 147
- a single 2.54 cm diameter jet at a momentum flux ratio, J, of 53

The J values were obtained from the average jet trajectory equation (3-2) to give the same physical trajectory in the flow model. Figure 3-47 shows the smoke pictures of these two jets. The jet centerline trajectories were almost identical.

Figures 3-48 and 3-49 show the profiles of steady state tracer concentration, average velocity and turbulence intensity for the 1.27 cm and 2.54 cm diameter jets respectively. Tracer measurements were made by

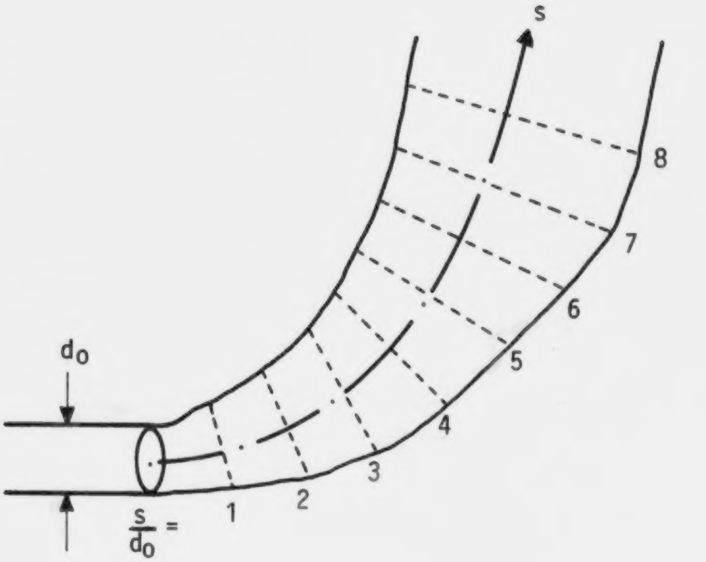
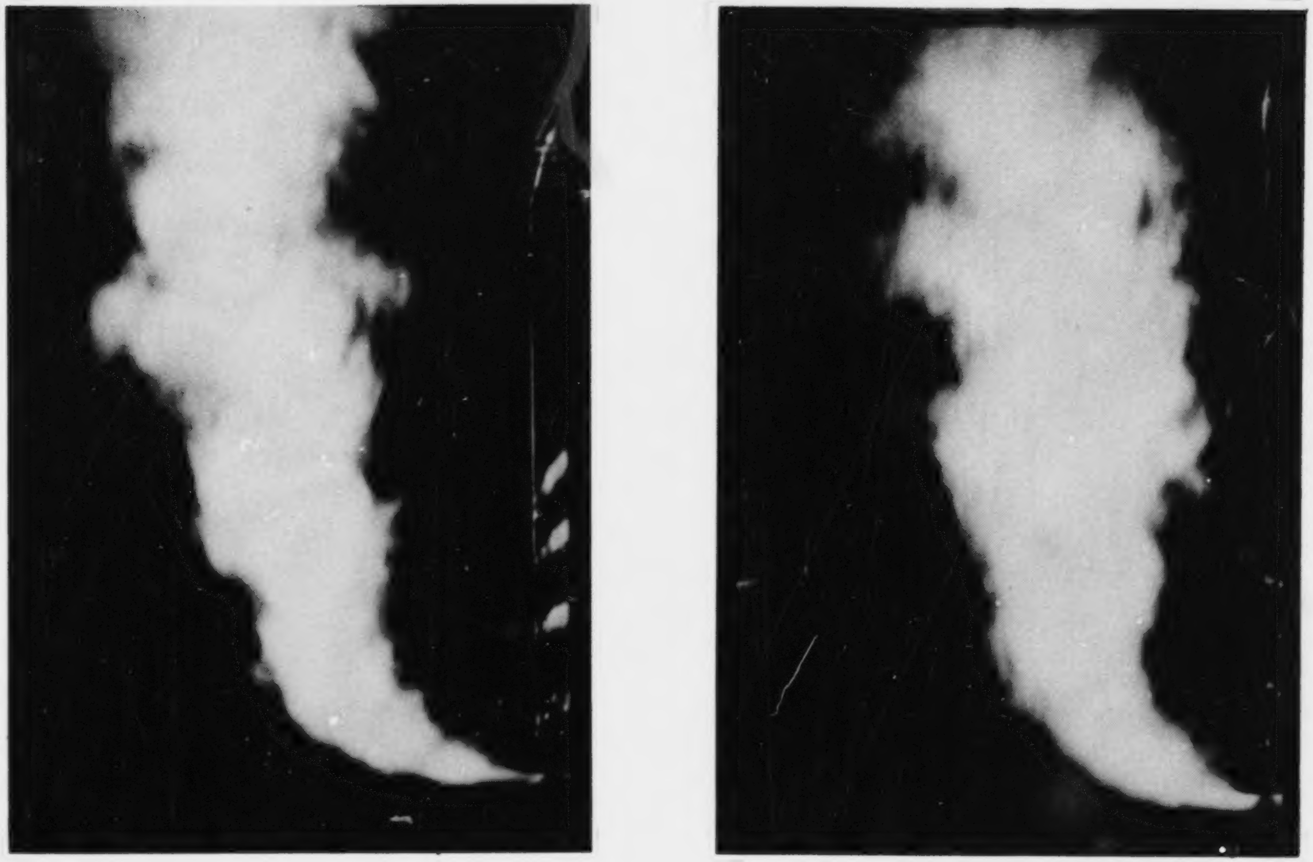

s
d_0
$\frac{s}{d_0}$ =
1
2
3
4
5
6
7
8

Figure 3-46. Region of the jets investigated for detailed velocity and tracer concentration profiles.



d_o = 1.27 cm, J = 147

d_o = 2.54 cm, J = 53

Figure 3-47. Smoke photographs of 1.27 cm and 2.54 cm of diameter jets in uniform cross flow.

d_o = 1.27 cm., V_o = 5.40 m/s, V_∞ = 0.45 m/s, J = 147, Profiles at s/d_o = 1.0

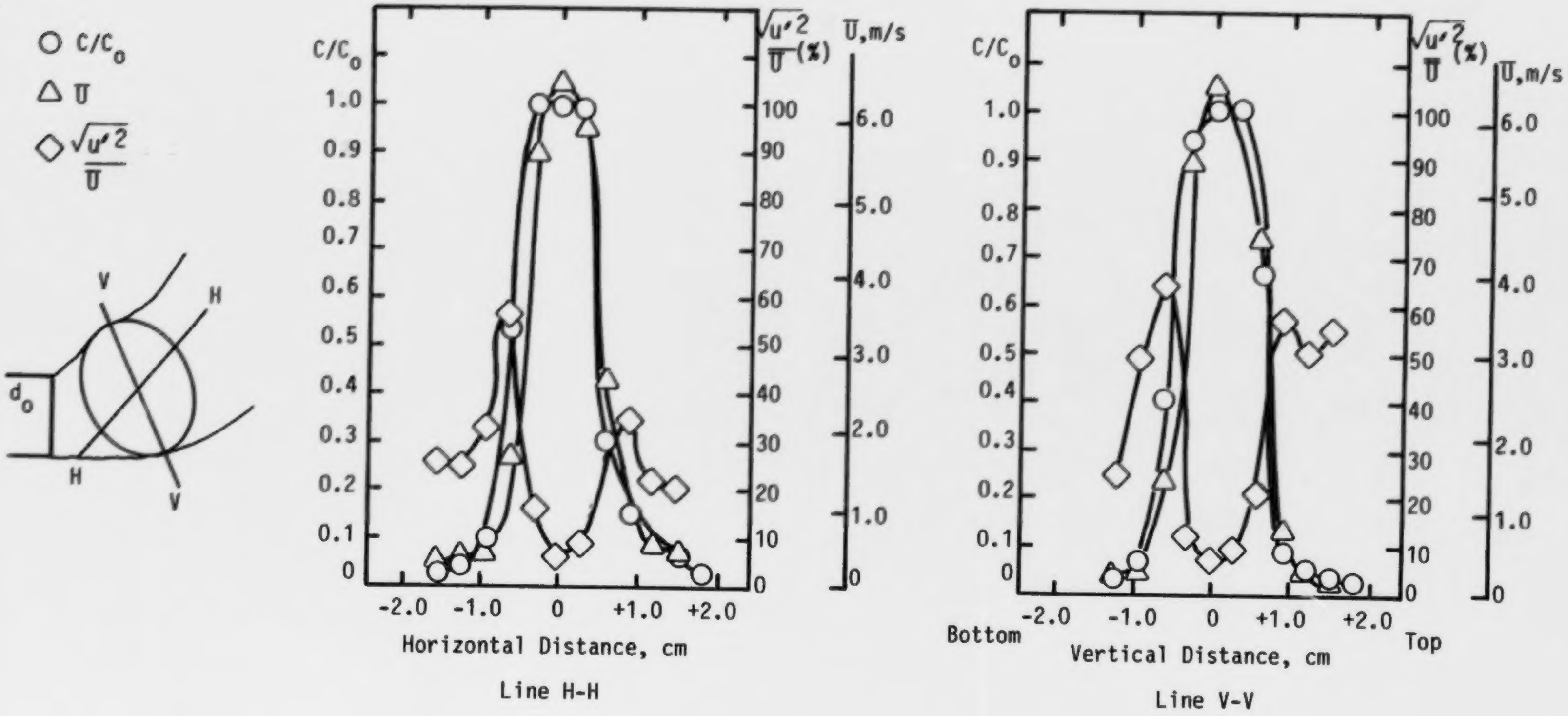


Figure 3-48a. Measured profiles of tracer concentration, velocity and turbulent intensity for a 1.27 cm. diameter jet at J = 147, s/d_o = 1.0.

d_o = 1.27 cm, V_o = 5.40 m/s, V_∞ = 0.45 m/s, J = 147, Profiles at s/d_o = 2

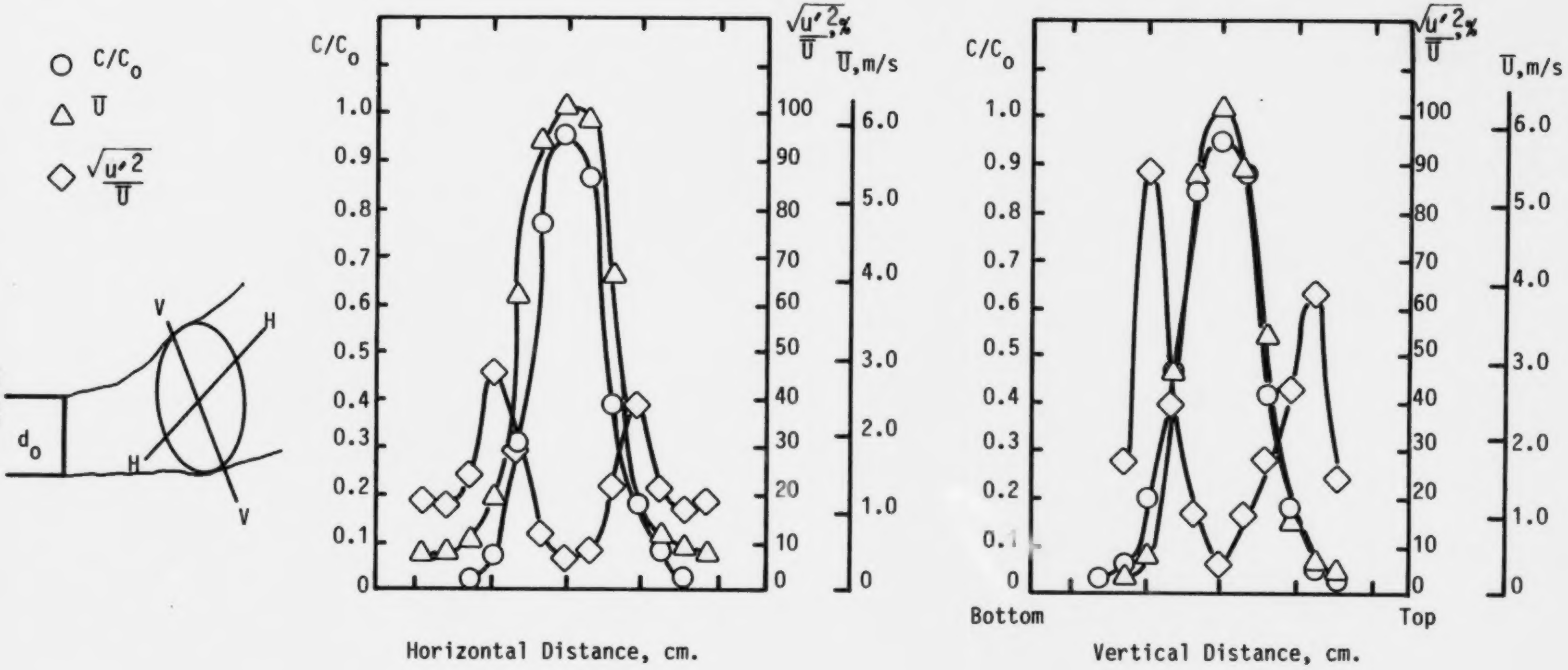


Figure 3-48b. Measured profiles of tracer concentration, velocity and turbulent intensity for a 1.27 cm. diameter jet at J = 147, s/d_o = 2.0.

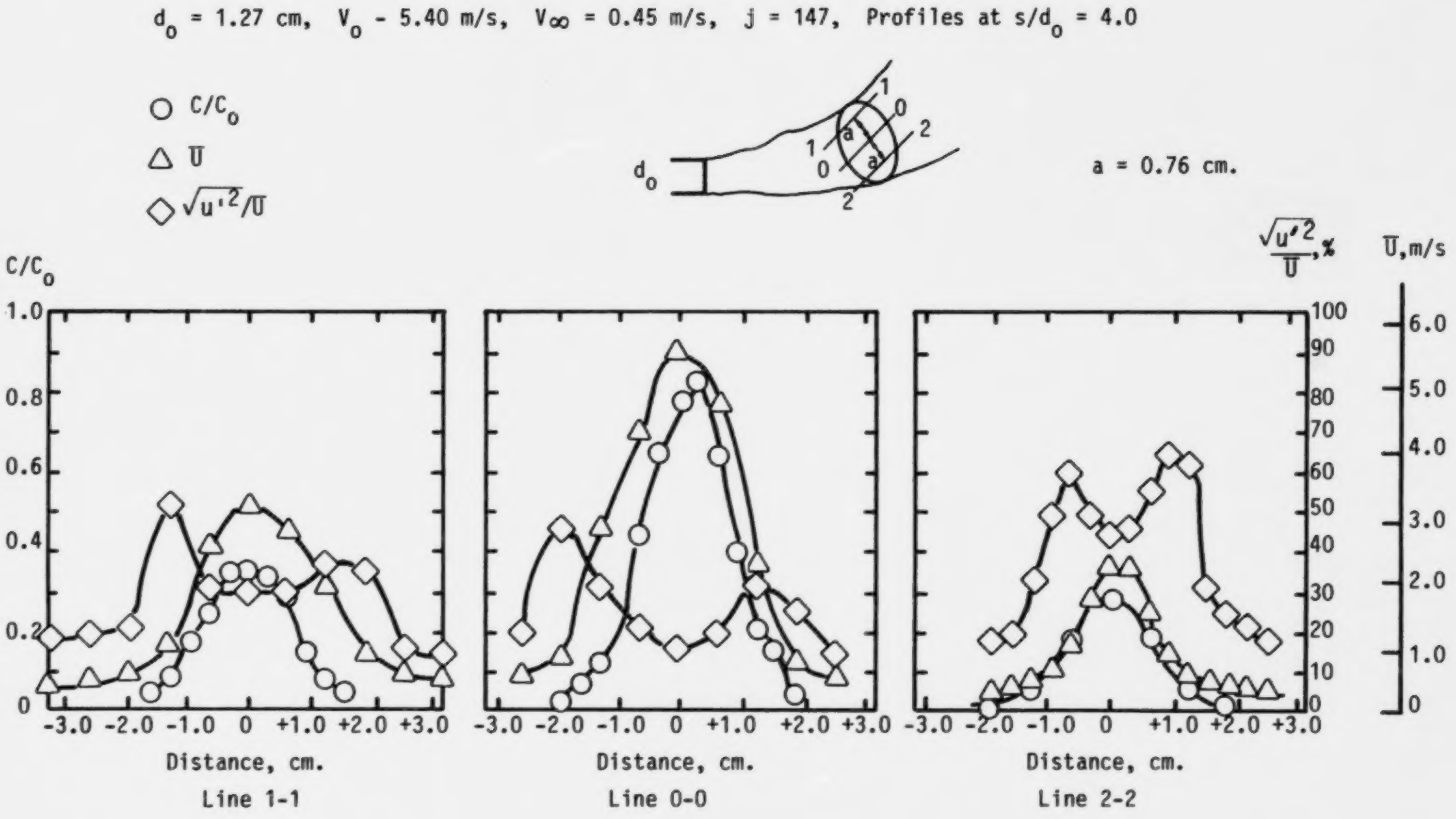


Figure 3-48c. Measured profiles of tracer concentration, velocity and turbulent intensity for a 1.27 cm. diameter jet at J = 147, s/d_o = 4.0.

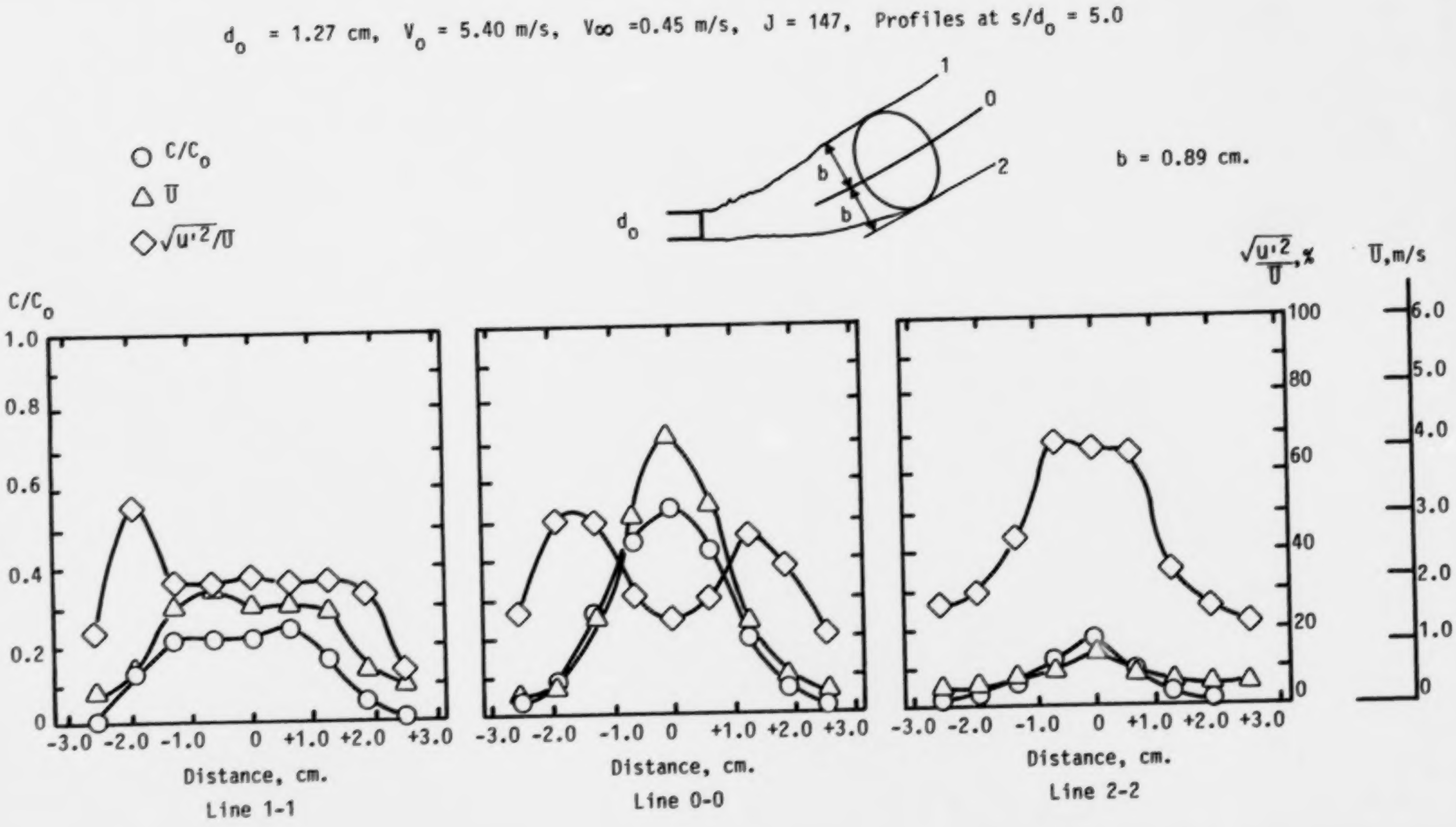


Figure 3-48d. Measured profiles of tracer concentration, velocity and turbulent intensity for a 1.27 cm. diameter jet at 147, s/d_o = 5.0.

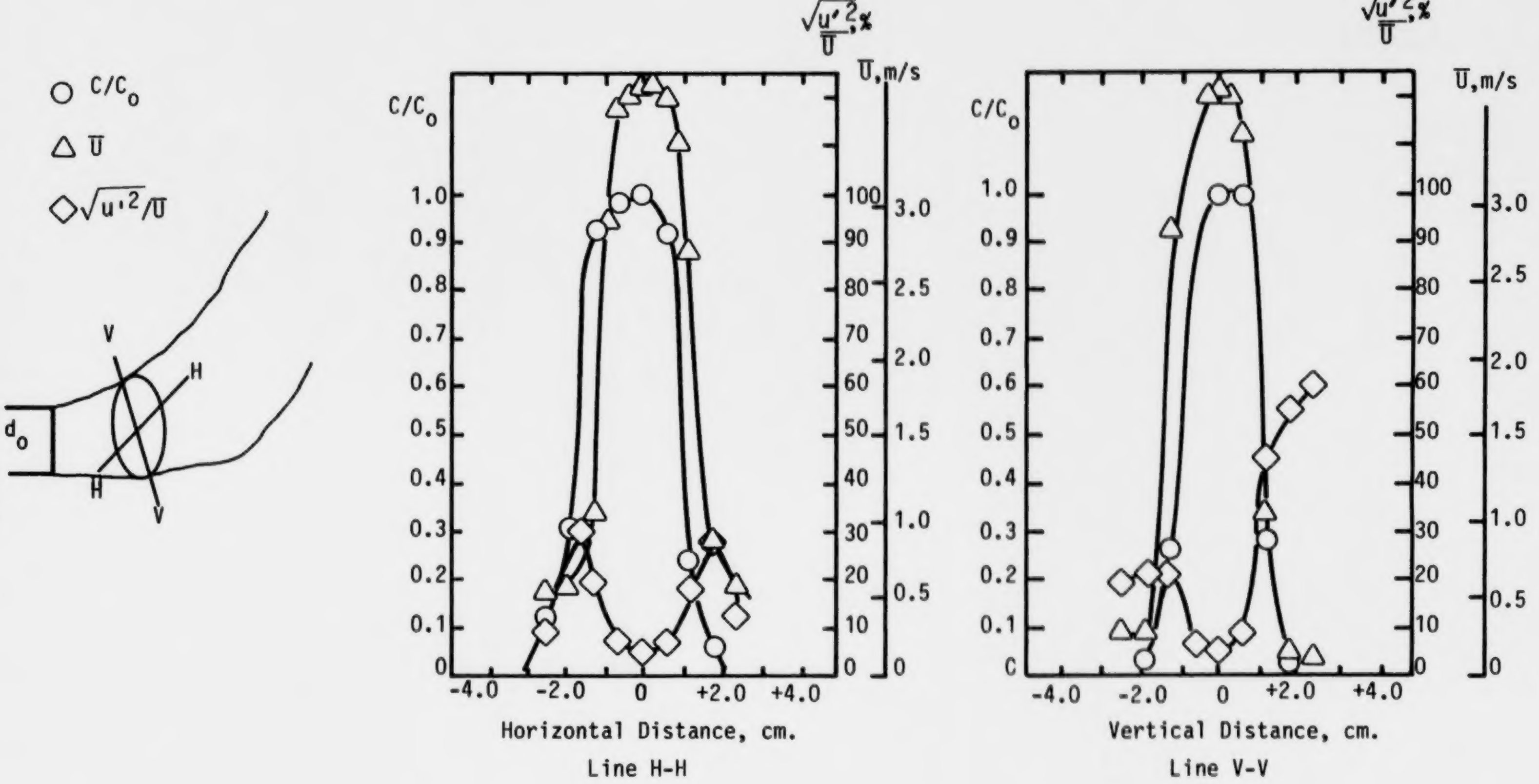


Figure 3-49a. Measured profiles of tracer concentration, velocity and turbulent intensity for a 2.54 cm. diameter jet at $J = 52.3$, $s/d_o = 1.0$.

d_o = 2.54 cm, V_o = 2.76 m/s, V_∞ = 0.38 m/s, J = 52.3, Profiles at s/d_o = 3.0

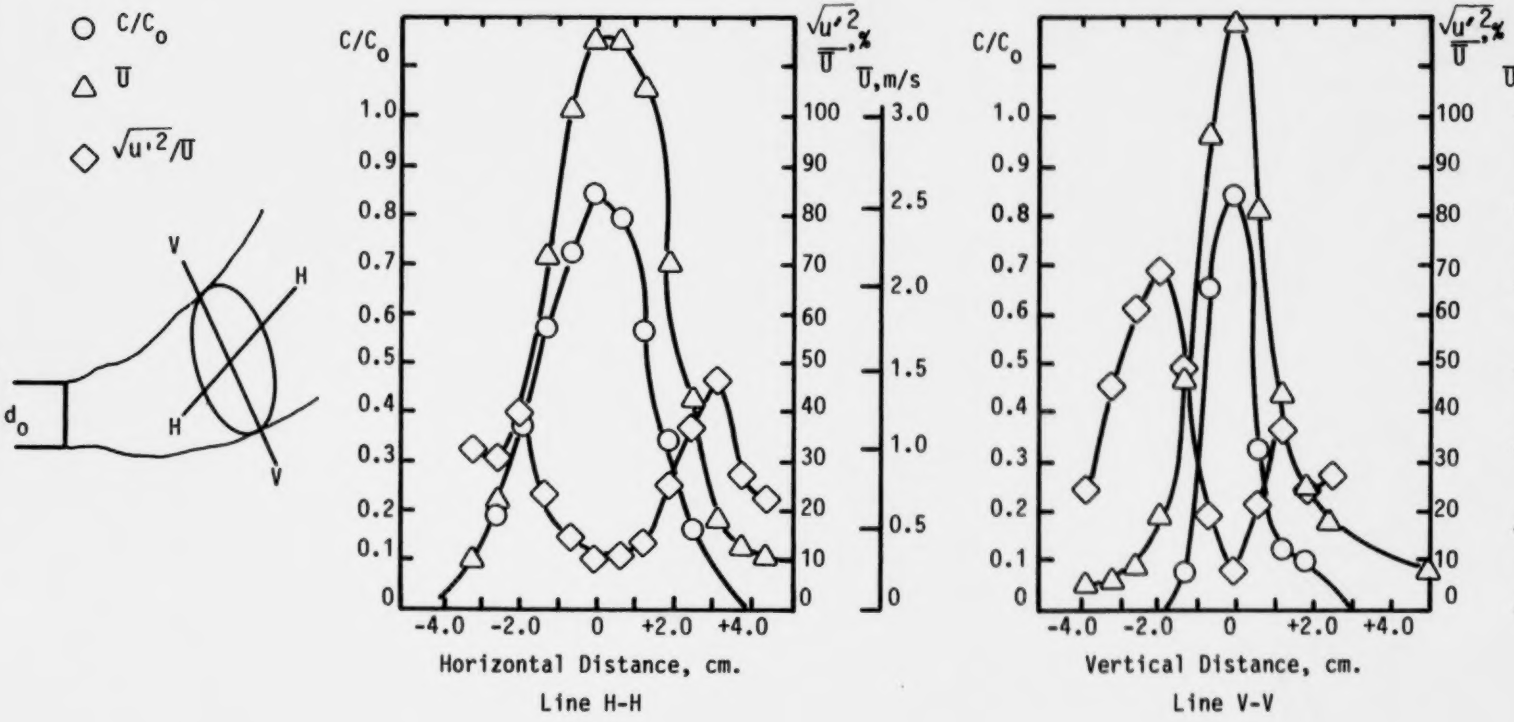


Figure 3-49b. Measured profiles of tracer concentration, velocity, and turbulent intensity for a 2.54 cm. diameter jet at J = 52.3, s/d_o = 3.0.

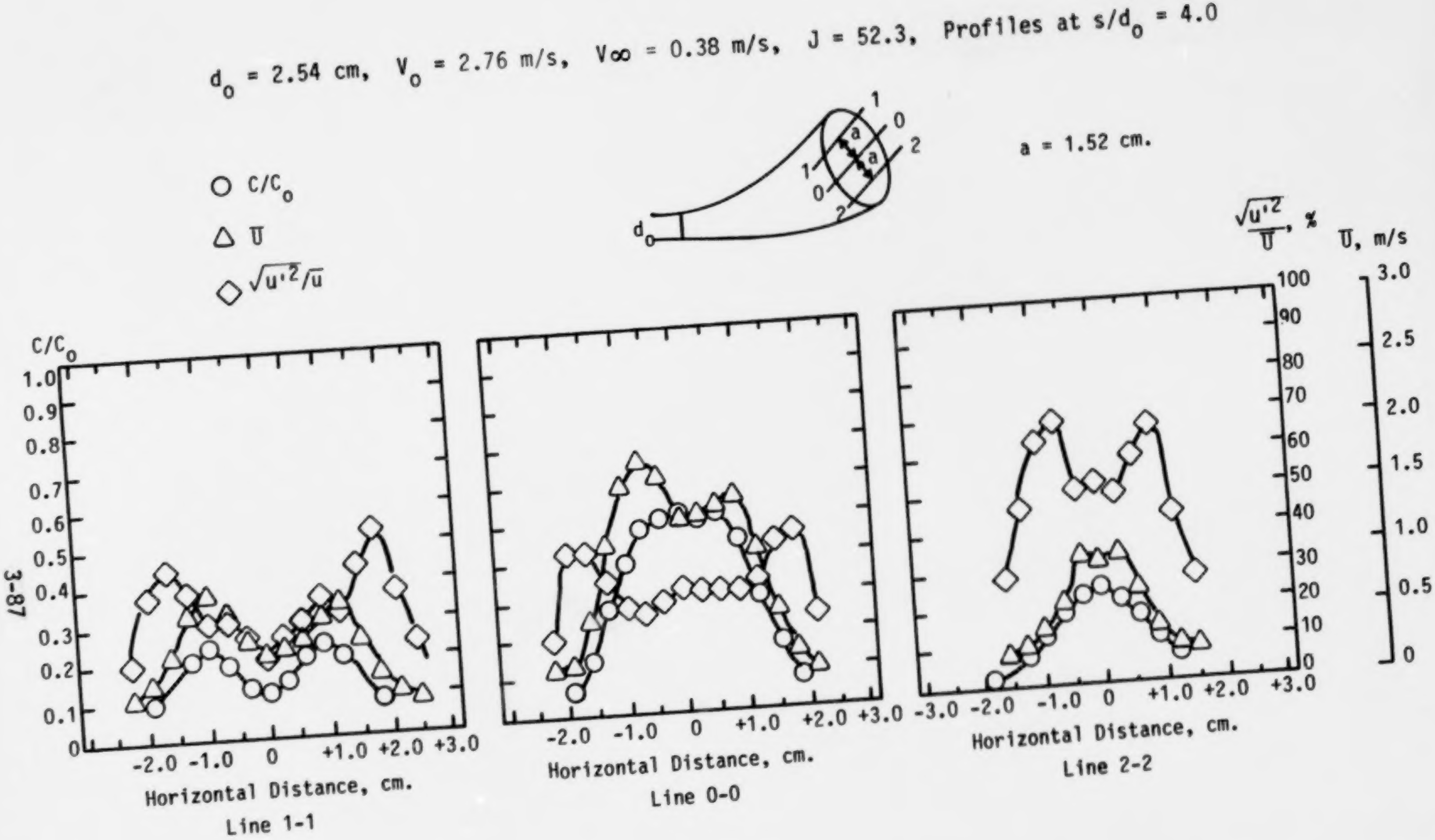


Figure 3-49c. Measured profiles of tracer concentration, velocity and turbulence intensity for a 2.54 cm. diameter jet at J = 52.3, $s/d_o = 4.0$.

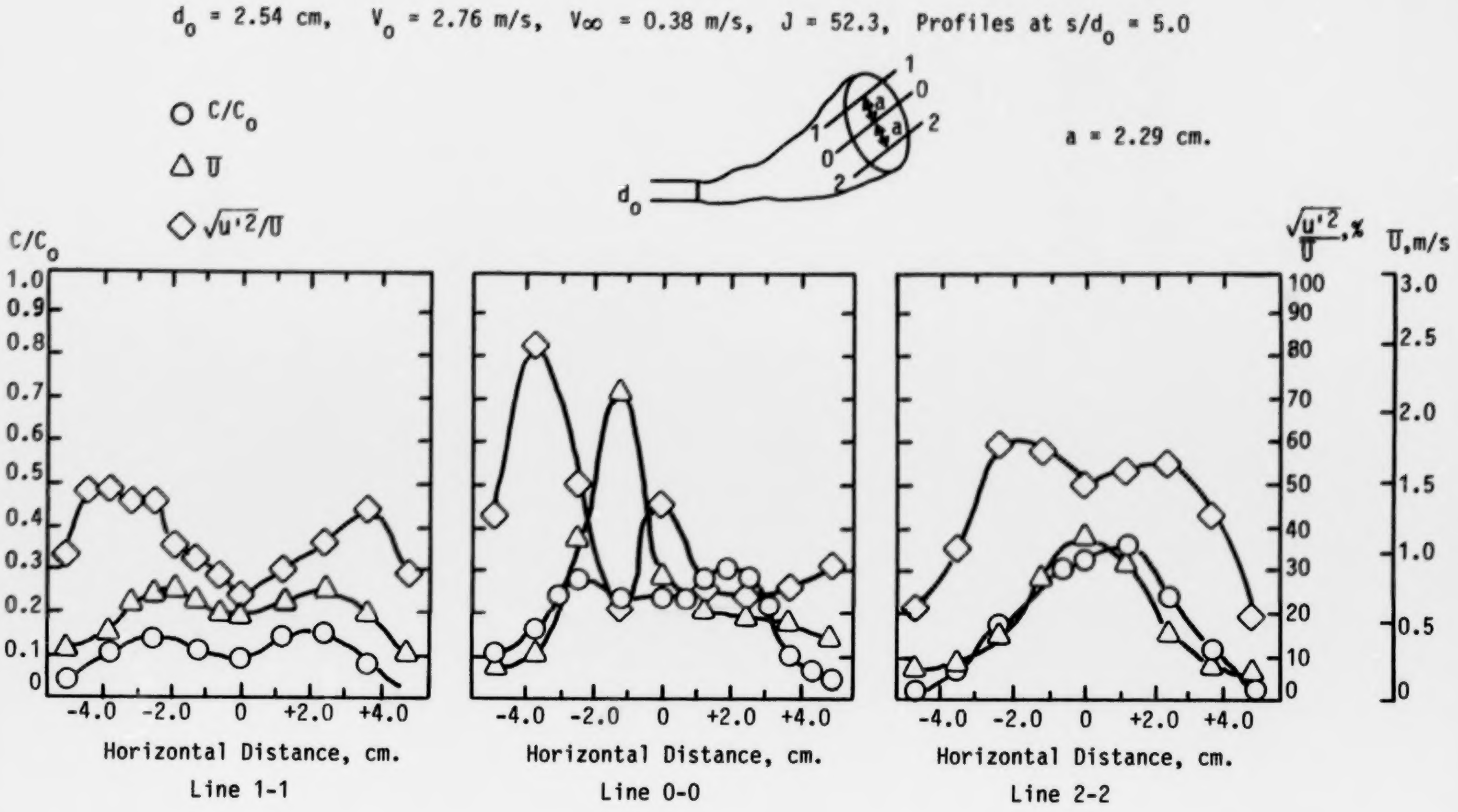


Figure 3-49d. Measured profiles of tracer concentration, velocity and turbulence intensity for a 2.54 cm. diameter jet at J = 52.3, s/d_o = 5.0

introducing a small amount of methane (CH_4) into the jet fluid and analyzing an extracted sample with an infrared analyzer. This was the same technique used in the dispersion measurements described earlier. The average velocity and turbulence intensity measurements were made with a single hot wire anemometer.

For the 1.27 cm diameter jet, measurements were made at four downstream locations; one, two, four and five diameters along the jet trajectory (s/d_0 = 1.0, 2.0, 4.0 and 5.0) as shown in Figure 3-48 a, b, c and d. In the near field of the jet ($s/d_0 = 1,2$), the velocity, $\bar{U}$, and concentration, C/C_0, profiles were bell-shaped in both horizontal and vertical direction. However, the turbulence intensities, $\sqrt{u'^2}/U$ showed two maxima on either side of the jet indicating the high turbulence levels in the shear zones at the boundaries of the jet. In the velocity profiles, the influence of the free stream velocity was not taken into account because the free stream velocity was an order of magnitude smaller than the jet velocities in the early part of the jet. This is apparent in Figures 3-48a and b where the measured jet velocities were around 6 m/s while the free stream velocity approached to values less than 0.5 m/s. Therefore, the measured velocities were believed to represent the forward normal velocity at the jet cross section. In order to evaluate the flow rates in the jet, a scalar quantity which decays to zero in the outer flow was required. Otherwise, the edge of the jet (the limit of integration) cannot be appropriately determined. This required the tracer concentration measurements which were used in conjunction with the velocity measurements to determine the total flow rates in the jets.

Figure 3-49 shows the distributions of tracer concentration, velocity and turbulence intensities for a 2.54 cm diameter jet in uniform cross flow. Similar characteristics of tracer, velocity and turbulence intensities were observed at s/d_0 = 1.0 and 3.0; namely, bell-shaped profiles of concentration and velocity and double-humped turbulence intensity profiles. At farther downstream locations, s/d_0 = 4.0 and 5.0, the velocity profiles also assumed a double-humped shape in the trailing edge of the jet. This was because of the kidney-shaped cross section of the jets within which the velocities were higher than the main flow. This was also confirmed by the tracer concentration profiles which had similar shapes. It should also be pointed out here that no attempt was made to resolve velocities to identify the internal recirculating flow field as this was not possible with the available measurements.

Based on the data presented above, graphical integrations were performed to obtain the following quantities

$$\frac{\overline{U}}{U_o} = \frac{\int_{A_j} \frac{U}{U_o}\, dA}{A_j} \tag{3-22}$$

$$\frac{\overline{C}}{C_o} = \frac{\int_{A_j} \frac{C}{C_o}\,\frac{U}{U_o}\, dA}{\frac{\overline{U}}{U_o} \cdot A_j} \tag{3-23}$$

$$\frac{\dot{Q}}{\dot{Q}_o} = \frac{\overline{U}}{U_o} \cdot \frac{A_j}{A_o} \tag{3-24}$$

The quantities on the left-hand side of these equations are those generated by the jet model presented in Section 4.0. In performing graphical integrations, the assumption was made that the profiles in the horizontal direction (see Figures 3-48a and 3-49a, line H-H) were self similar, with peak variation given by the vertical profiles. This assumption is reasonable on the grounds that the jets were symmetric in the horizontal direction, i.e. the centerline of symmetry of the kidney-shaped jet. The integrated quantities in equations (3-22) through (3-24) are tabulated in Tables 3-6 and 3-7 for 1.27 cm and 2.54 cm diameter jets. The result from these evaluations will be compared with predictions from a computational jet model in the next section.

TABLE 3-6. INTEGRATED JET PARAMETERS FOR 1.27 CM. DIAMETER JET AT J = 174

s/d_o	1.00	2.00	3.00	4.00	5.00
$\frac{1}{A_j}\int \frac{u}{u_o}\, dA$	0.479	0.470	0.329	0.452	0.290
$\frac{1}{A_j}\int \frac{u}{u_o}\frac{C}{C_o}\, dA$	0.337	0.243	0.170	0.216	0.089
$\bar{C}/C_o$	0.703	0.518	0.517	0.479	0.305
$\dot{Q}/\dot{Q}_o$	1.268	1.580	1.645	2.580	—

TABLE 3-7. INTEGRATED JET PARAMETERS FOR 2.54 CM. DIAMETER JET AT J = 53

s/d_o	1.00	3.00	4.00	5.00
$\frac{1}{A_j}\int \frac{u}{u_o}\,dA$	0.436	0.333	0.224	0.191
$\frac{1}{A_j}\int \frac{u}{u_o}\,\frac{C}{C_o}\,dA$	0.261	0.138	0.074	0.041
$\bar{C}/C_o$	0.599	0.414	0.330	0.215
$\dot{Q}/\dot{Q}_o$	1.36	1.74	2.04	3.35

3.4 Summary of Isothermal Tests

Experiments in a boiler upper furnace flow cell and an alternate configuration test model were conducted in order to understand the key features of jet injection. The key results from the upper furnace flow cell can be summarized as follows:

- The two key jet parameters determining the jet trajectory in boiler like flow fields are the jet-to-cross-flow momentum flux ratio and the jet diameter.

- Smoke traces of the injection jets provide useful information on the jet dispersion in the main flow.

- Comparison of smoke traces with tracer concentration measurements indicate that the leading edge of the jet is unambiguously marked by the smoke. However, the trailing edge can be misinterpreted from the smoke trace because of the low smoke density with measureable jet fluid in the unmarked regions.

- For typical injection configurations, the side spacing of multiple jets, and the depth confinement parameters, appear to have a negligible impact on the jet trajectories. Hence, correlations developed for a single jet in unbounded surroundings can be used.

- In the flow field of the boiler around the nose, the initial bending of jets injected from the front wall can be well predicted by the average jet trajectory equation. However, as the furnace flow turns into the horizontal passes, the jet trajectory deviates from the predictions.

- Injection from the rear wall at the nose location can be an effective way to introduce the sorbent in the bulk of the flow near the nose. However, this region of the boiler is generally inaccessible.

- Injection from the roof of the boiler, or highly down-angled (greater than 70° from horizontal) injection from the front wall, requires very high injection velocities to achieve penetration through the opposing flow to a stagnation level at the favorable temperature zone. Although roof injection may be a viable means to control the injection temperature, the high velocities required may make it impractical. There also appears to be marginal or no gain in residence time due to increased path of the jet because of the high injection velocities.

- Effects of sorbent particles can be incorporated in the bulk jet properties, i.e. jet density and momentum. Photographic evidence and particle dispersion measurements supported this view. Provided that sorbent particles are small (less than 20 microns in size), and the particle loadings are not high (less than 10^7 particles/cc), the dispersion characteristics of particle laden jets and equivalent air jets are similar.

Tests performed in an alternate configuration model revealed the following results:

- It was found that the trajectories of the jets injected from the front wall were affected by enclosure characteristics such as the nose confinement factor and the injection location in relation to the nose point. This is expected since the enclosure geometry determines the main flow characteristics which impact the jet behavior.

- Simulation of cold, dense jets injected into a hot combustion environment in an isothermal study required the modification of the jet diameter with the square root of the jet to free stream density ratio if near field dilution rates were to be properly simulated. However, in the far field (greater than 10-15 jet diameters from the jet nozzle), different scaling approaches gave similar results. For example, geometric scaling of jet diameters could be employed.

- Comparison of measured isothermal and combustion dispersion patterns suggested approximate similarity of the dispersion patterns with similar distributions of the tracer concentrations.

- Finally, the detailed measurements were conducted for two isothermal jets in uniform cross-flow. The measurements of tracer concentration, velocity and turbulence intensity all showed expected behavior. These measurements were utilized to calibrate a computational model of a jet in cross-flow described in the next section.

4.0 COMPUTATIONAL MODEL OF A JET IN CROSS-FLOW

The previous section described experimental studies of cross-flow jet injection in boiler geometries. Review of literature on entrainment of jets injected into a cross-flow stream, which determines the mixing characteristics, revealed that very little information on the entrainment rates of jets in cross flow was available. A knowledge of the entrainment behavior of a jet in cross flow is very important to the problem under study for several reasons. These include:

- The bending characteristics of a jet in cross flow is closely correlated with its entrainment. Penetration of the injection jets into the the furnace flow is one of the key criteria in the design of a sorbent injection system.

- Entrainment of the hot furnace gas stream into the jet containing the sorbent determines the heat-up rates of the sorbent particles as well as the variation of partial pressure of SO_2 around the particles. This requires a knowledge of the near field behavior of cross-flow jet entrainment.

- Entrainment of the jets also determines the mixing of the furnace flow with the jets. Hence, it is of importance for SO_2 capture.

The most straightforward method of determining entrainment of a jet in cross flow would be by conducting a series of experiments with the key jet parameters as variables. Along this line of thinking, several investigations, reported in the literature, have (9,10) involved detailed characterization of temperature and velocity distributions at several jet cross-sections downstream of the injection point. In particular, Kamotani and Greber (9) attempted to integrate the velocity-density product at several jet cross sections to determine the entrainment rates of a jet in cross-flow. Their results, shown in Figure 4-1, indicated that the entrainment was an increasing function of the jet to cross-flow momentum flux ratio. Although their results correctly indicated that the entrainment of a jet in cross flow

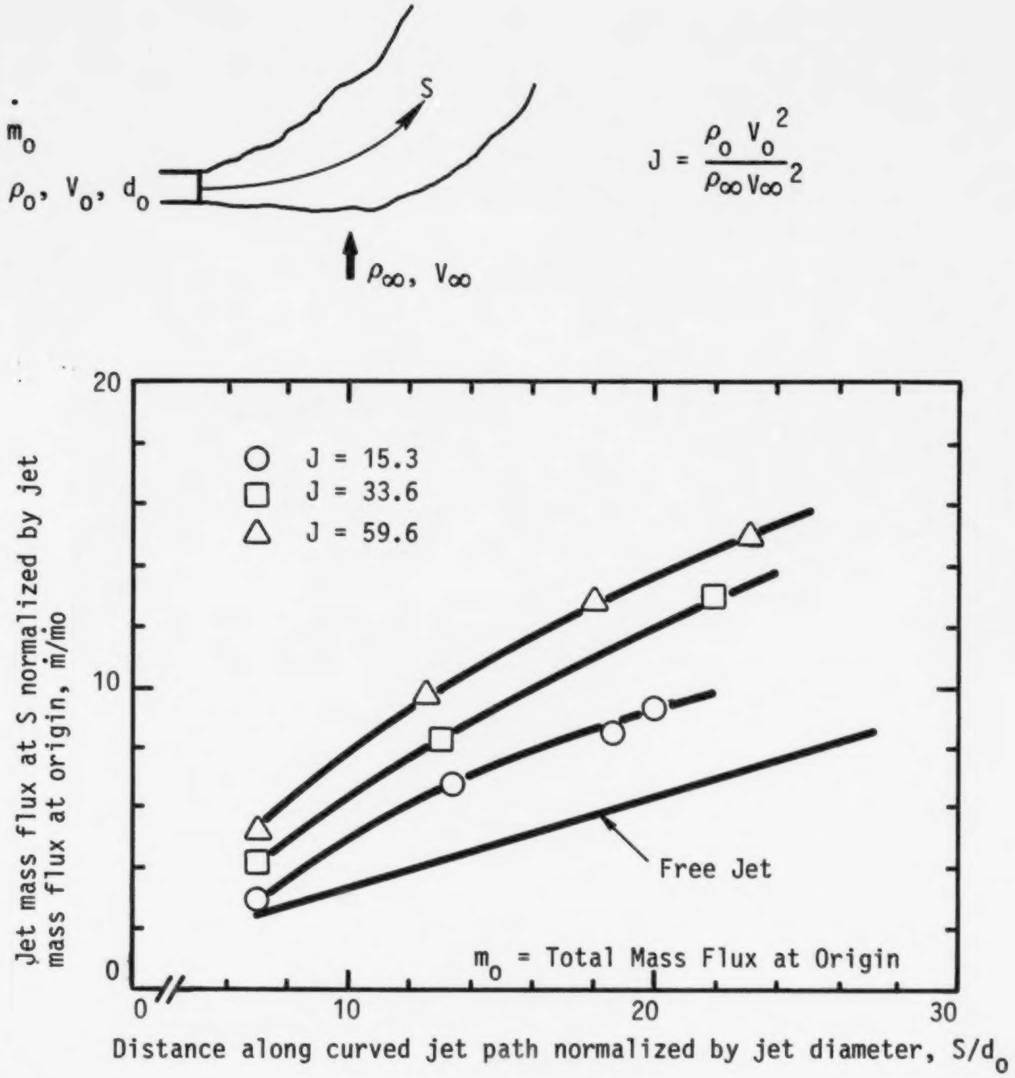


Figure 4-1. Data obtained from the work of Kamotani and Greber (9).

is higher than that of a free turbulent jet, the dependence on the momentum flux ratio contradicts the expected trend. As the momentum flux ratio increases (or as the free stream velocity decreases), it is expected that the conditions approach asymtotically to the free turbulent jet, and the decrease in the shear due to the lower cross-flow velocity would result in a reduction of the entrainment rates. This is opposite to the trend shown in Figure 4-1. It is possible that such behavior stems from the difficulties in interpretation of the measurements used to determine the flow rates in the jets. For example, the method based on integration of velocity-density product across the jet cross section suffers from the uncertainty associated with the high degree of fluctuations in both velocity and density near the edges of the jet. This uncertainty is further amplified because of the larger area increments in the integration near the edges of the jet. Also, determination of the jet boundaries becomes more difficult for a jet in cross flow. These aforementioned difficulties make entrainment measurements based on such methods very inaccurate, even in the case of a free turbulent jet.

Entrainment measurements for a free turbulent jet were made by Ricou and Spalding (17) based on a mass conservation technique which did not suffer from the difficulties mentioned above. However, implementation of their method is not possible for cross flow jet injection due to the presence of the outer flow and the resulting curvature of the jet. Because of the experimental difficulties, a different approach was taken here to determine the bulk development of a jet in cross flow. The intention was to develop a simple computational model of jet injection into a cross flow which could be validated by carefully conducted experiments and data from literature. This was also desirable since it would constitute part of the sorbent injection system design methodology, the goal of this project. In the following, the formulation of the model for a jet injected at right angles to a uniform cross flow is described first. This is followed by the calibration of the model with experimental data. With the calibrated model of jet injection into uniform cross flow, the model extension to turning, accelerating flow field (reminiscent of the boiler flow) is considered in Subsection 4.3. Finally, the results from modeling and their use in conjunction with the available calcination/sulfation models are discussed in Subsection 4.4.

4.1 Formulation of Jet Injection into Uniform Cross-Flow

The model formulated here is an integral model of a jet in cross flow which predicts the bulk jet characteristics based on mass, momentum and energy balances. It is fundamentally similar to other such models (19,20) however it differs in the way the entrainment model is calibrated. The essential feature of this model is the integration of jet properties across the jet cross-sections (transverse direction) which reduces the equations of motion and energy to those governing the streamwise variation of these properties. Figure 4-2 shows the jet configuration and the coordinate systems associated with the jet nozzle. If a slice normal to the jet path is taken, then the conservation of mass can be written in an integral-differential form with a prescribed entrainment law as,

$$\frac{d}{ds}\left[\int_A \rho u dA\right] = \rho_\infty \mathscr{P}(\alpha|u - V_t| + \beta|V_n| \qquad (4\text{-}1)$$

The various jet quantities are defined in Figure 4-2. $\mathscr{P}$ is the jet perimeter. α and β are empirical constants. This equation simply states that the rate of change of mass along the jet (left-hand side) is due to the entrainment of outer flow fluid into the expanding jet in the shear zones. The assumed entrainment law postulates that entrainment is driven by the tangential $(u - V_t)$ and transverse (V_n) velocity gradients independently. This assumption has been used many times quite successfully although it does not take account of the internal recirculation and the wake present in the jet. In the case of a free turbulent jet, the cross-flow entrainment term, $\beta|V_n|$, vanishes and the classical entrainment representation for a free turbulent jet is recovered (see references (16,20,21,22).

The two momentum equations, describing the momentum transfer in streamwise and transverse directions can be written as:

$$\frac{d}{ds}\left[\int_A \rho u^2 dA\right] = V_t \frac{d}{ds}\left[\int_A \rho u dA\right] + g \cos\theta \int_A (\rho_\infty - \rho)\, dA \qquad (4\text{-}2)$$

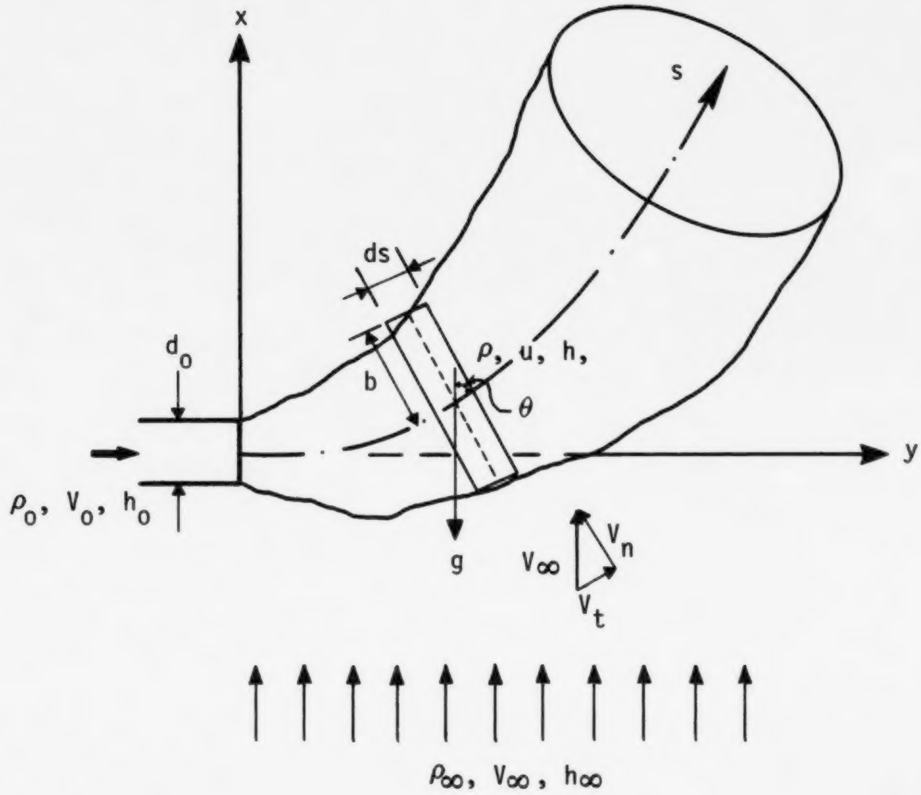

x
s
ds
d_o
ρ, u, h,
b
θ
y
ρ_o, V_o, h_o
g
V_∞
V_n
V_t
ρ_∞, V_∞, h_∞

Figure 4-2. Configuration of a jet in uniform cross flow and its associated coordinate systems.

$$\left[\int_A \rho u^2 dA\right]\frac{d\theta}{ds} = -V_n \frac{d}{ds}\left[\int_A \rho u dA\right] + g \operatorname{Sin}\theta \int (\rho_\infty - \rho)\, dA - \frac{dF_d}{ds} \qquad (4\text{-}3)$$

In these equations, the left-hand sides represent the axial and centrifugal accelerations of the jet while the right-hand sides are the forces which induce these accelerations. The first terms represent the entrained momenta into the jet. The second terms represent the effect of the buoyancy forces. These have been taken into account although they are negligible in most cases studied here. The third term in equation (4-3) is a simplified description of the effect of the pressure forces generated around the jet by the cross flow. This can be visualized as a form drag term. In the subsequent analysis, this term was not implemented in the calculations. Rather, the effect of this term was incorporated in the momentum entrainment term. Finally, the forces imposed on the jet by the pressure gradients generated in the outer flow were neglected, since the pressure in the flow under consideration was approximately constant.

The thermal energy equation was written as,

$$\frac{d}{ds}\left[\int_A \rho u^2 h dA\right] = h_\infty\left[\int_A \rho u dA\right] - \frac{dq_L}{ds} \qquad (4\text{-}4)$$

This equation expresses the change in the enthalpy flux of the jet which is strictly caused by entrainment and a heat loss term to the surroundings (a necessary element in considering boiler thermal environment with temperature decay due to heat loss to the cool enclosure walls). The thermal energy contributions from the work terms such as those due to buoyancy and drag forces were determined to be small for the cases of interest. Therefore, they were neglected in the energy equation.

In order to complete the formulation of the problem, the ideal gas law was used as the equation of state. Because the interest lies in prediction of particle-laden jets, an approximation was made in the ideal gas law by assuming that the particle-laden gas can be treated as a pseudo-ideal gas with an equivalent molecular weight and density.

4.2 Assumptions and Simplifications

The general formulation of the problem presented in the previous subsection does not allow a solution, unless further assumptions and simplifications can be made. Two key assumptions, in addition to those made earlier, were implemented to facilitate a solution of the governing equations. These were:

- Jet cross sections remain circular along the jet. Although it is known that jet assumes a kidney-shaped cross section, this assumption is a reasonable one for a first order treatment.

- Profiles of velocity, u, density, ρ, and enthalpy, h, the latter two of which are related by the equation of state, can be approximated by uniform "top-hat"(*) profiles. This assumption is probably more severe than the first one since these quantities exhibit significant variations in the jet. However, it is a reasonable assumption in order to obtain the bulk characteristics of the jet. Assumption of more detailed profiles requires a much more involved analysis which is beyond the simple analysis intended here.

Incorporating these two assumptions in equations (4-1), (4-2), (4-3) and (4-4) and carrying out the integrations, the results become,

$$\frac{d}{ds}(\pi \rho u b^2) = 2\pi b \rho_\infty \; (\alpha |u - V_t| + \beta |V_n|) \qquad (4\text{-}5)$$

(*) "Top hat" profile is a commonly used term for constant, uniform profiles References 20, 21, 22

$$\frac{d}{ds}(\pi\rho u^2 b^2) = V_t \frac{d}{ds}(\pi\rho u b^2) + \pi b^2 g \operatorname{Cos}\theta\,(\rho_\infty - \rho) \tag{4-6}$$

$$(\pi\rho u^2 b^2)\frac{d\theta}{ds} = -V_n \frac{d}{ds}(\pi\rho u b^2) - \pi b^2 g \operatorname{Sin}\theta\,(\rho_\infty - \rho) \tag{4-7}$$

$$\frac{d}{ds}(\pi\rho u h b^2) = h_\infty \frac{d}{ds}(\pi\rho u b^2) - \frac{dq_L}{ds} \tag{4-8}$$

for mass, streamwise and normal momenta and thermal energy respectively. Here, $h \equiv C_pT$ and ρ is given by $\rho = P\mathcal{M}/RT$ where P is pressure, $\mathcal{M}$ is mixture molecular weight, R is universal gas constant and T is temperature. b is the radius of the jet as shown in Figure 4-2.

Most efficient way of obtaining a solution of these equations requires nondimensionalization of velocities, densities and distances with respect to reference values for these quantities. The reference values, selected for nondimensionalization, were the values at the jet orifice, namely, U_o, ρ_o, r_o. Defining the following parameters:

$$\xi = \frac{s}{r_o}, \quad M = \frac{\pi\rho u b^2}{\pi\rho_o U_o r_o^2}, \quad G = \frac{\pi\rho u^2 b^2}{\pi\rho_o U_o^2 r_o^2}$$
$$Q = \frac{T}{T_o}, \quad Fr = \frac{g r_o}{U_o^2}, \quad X = \frac{x}{r_o}, \quad Y = \frac{y}{r_o} \tag{4-9}$$

and nondimensionalizing takes these equations into the following forms:

$$\frac{dM}{d\xi} = 2\left(\frac{b}{r_o}\right)\left(\frac{\rho_\infty}{\rho_o}\right)\left\{\alpha\left|\frac{G}{M} - \frac{V_t}{U_o}\right| + \beta\left|\frac{V_n}{U_o}\right|\right\} \tag{4-10}$$

$$\frac{dG}{d\xi} = \frac{V_t}{U_0}\frac{dM}{d\xi} + Fr\left(\frac{b}{r_0}\right)^2\left(\frac{\rho_\infty - \rho}{\rho_0}\right)\cos\theta \qquad (4\text{-}11)$$

$$G\frac{d\theta}{d\xi} = -\frac{V_n}{U_0}\frac{dM}{d\xi} - Fr\left(\frac{b}{r_0}\right)^2\left(\frac{\rho_\infty - \rho}{\rho_0}\right)\sin\theta \qquad (4\text{-}12)$$

$$\frac{d}{d\xi}(MQ) = Q_\infty\frac{dM}{d\xi} - \frac{dq_L}{d\xi} \qquad (4\text{-}13)$$

These equations describe the variations of the bulk jet parameters along the trajectory of the jet. They are ordinary differential equations which can be integrated numerically by Runge-Kutta integration technique (23), provided that initial conditions are prescribed. The initial conditions are:

$M(o) = 1$
$G(o) = 1$
$\theta(o) = \theta_0$ for normal injection $\theta_0 = \pi/2$
$Q(o) = 1$

The auxiliary relations also required for solution are:

$$\mathcal{M}_0 = \frac{1}{\dfrac{W_{os}}{\mathcal{M}_{os}} + \dfrac{(1 - W_{os})}{\mathcal{M}_{og}}} \qquad (4\text{-}14)$$

where $\mathcal{M}_0$ is the initial molecular weight of the jet. W_{os} is the mass fraction of the solid. The variation of the molecular weight in the jet can be expressed as:

$$\mathcal{M} = \frac{1}{\dfrac{1}{\mathcal{M}_0\dot{m}} + \dfrac{\dot{m}-1}{\mathcal{M}_\infty\dot{m}}} \qquad (4\text{-}15)$$

where m is the mass flow in the jet.

Other auxiliary relationships for the jet parameters can be listed as

$$\frac{U}{U_0} = \frac{G}{M}$$

$$\frac{\mathcal{M}}{\mathcal{M}_0} = \frac{\dot{m}}{1 + (\dot{m}+1)\dfrac{\mathcal{M}_0}{\mathcal{M}_\infty}}$$

$$\frac{\rho}{\rho_0} = \left(\frac{M}{M_0}\right) \frac{1}{Q}$$

$$\frac{\rho_\infty}{P_0} = \left(\frac{M_\infty}{M_0}\right) \frac{1}{Q_\infty}$$

$$\frac{b}{r_0} = \sqrt{M \left(\frac{\rho_0}{\rho}\right) \left(\frac{U_0}{U}\right)}$$

The jet trajectory is calculated from

$$\frac{dX}{d\xi} = \text{Cos}\ \theta$$

$$\frac{dY}{d\xi} = \text{Sin}\ \theta \qquad (4\text{-}17)$$

The solution of the ordinary differential equations with the auxiliary expressions requires the following inputs:

- Initial values of M, G, θ, Q

- Initial jet to cross flow density (including effect of particles) and velocity ratios

- Other inputs such as integration step sizes, convergence parameters, etc.

The numerical solution by the code named JICFIS (Jets In Cross Flow Integral Solution) provides

- Non-dimensional jet trajectory x/r_0 versus y/r_0

- Variations of M, G, θ and Q along the jet

- Velocity and time along the jet trajectory (derived from the quantities above)

4.3 Determination of Entrainment Constants

The final task before a solution could be obtained is the determination of the two entrainment constants, α and β in equation (4-10) before the numerical integration of these equations can be performed. Because of the selected form of the entrainment expression, it can be seen that the entrainment constant α should approach that of a free turbulent jet in the limit the cross flow velocity approaches zero. This facilitated determination of the constant α from the empirical entrainment law for a free turbulent jet given by equation,

$$\frac{\dot{M}}{\dot{M}_0} = 0.32 \left(\frac{\rho_\infty}{\rho_0}\right)^{1/2} \frac{s}{d_0} \qquad (4\text{-}18)$$

Utilizing this expression and noting that the axial momentum in a free turbulent jet is conserved, i.e.

$$\rho_0 U_0^2 d_0^2 = \rho U^2 d^2 \qquad (4\text{-}19)$$

Equations (4-18) and (4-19) can be combined with equation (4-5) after some algebra to obtain

$$\alpha = 0.08 \left(\frac{\rho}{\rho_\infty}\right)^{1/2} \qquad (4\text{-}20)$$

Furthermore, due to the presence of a jet potential core, the entrainment rate should approach to the far field entrainment rate given by equation (4-20) in a smooth fashion. This was achieved by using an exponentially decaying suppression function which modifies the equation (4-20) as,

$$\alpha = 0.08 \left(\frac{\rho}{\rho_\infty}\right)^{1/2} \left\{ 1 - \exp\left[-0.32 \left(\frac{\rho_\infty}{\rho_0}\right)^{1/2} \frac{\xi}{2}\right] \right\} \qquad (4\text{-}21)$$

At this point, the only remaining parameter to be determined is the second entrainment coefficient, β, which reflects the contribution of the normal entrainment component. This constant was assumed to be a function of the jet to cross flow momentum flux ratio. In the present work, a power-law dependence of β on the momentum flux ratio was selected.

$$\beta = a\, J^b \qquad (4\text{-}22)$$

where a and b are empirical constants and J is $\rho_0 V_0^2/\rho_\infty V_\infty^2$. It should be pointed out that the functional behavior of β should be such that the term containing β in equation (4-10) should vanish in the asymptotic limit as $J \rightarrow \infty$. This requires that $b < 0.5$.

The procedure used to determine the function β was to match the jet trajectory by varying β. The values of β which gave the best match of the calculated and the experimentally determined jet trajectories, were plotted as a function of J on a log-log plot in Figure 4-3. Five J values

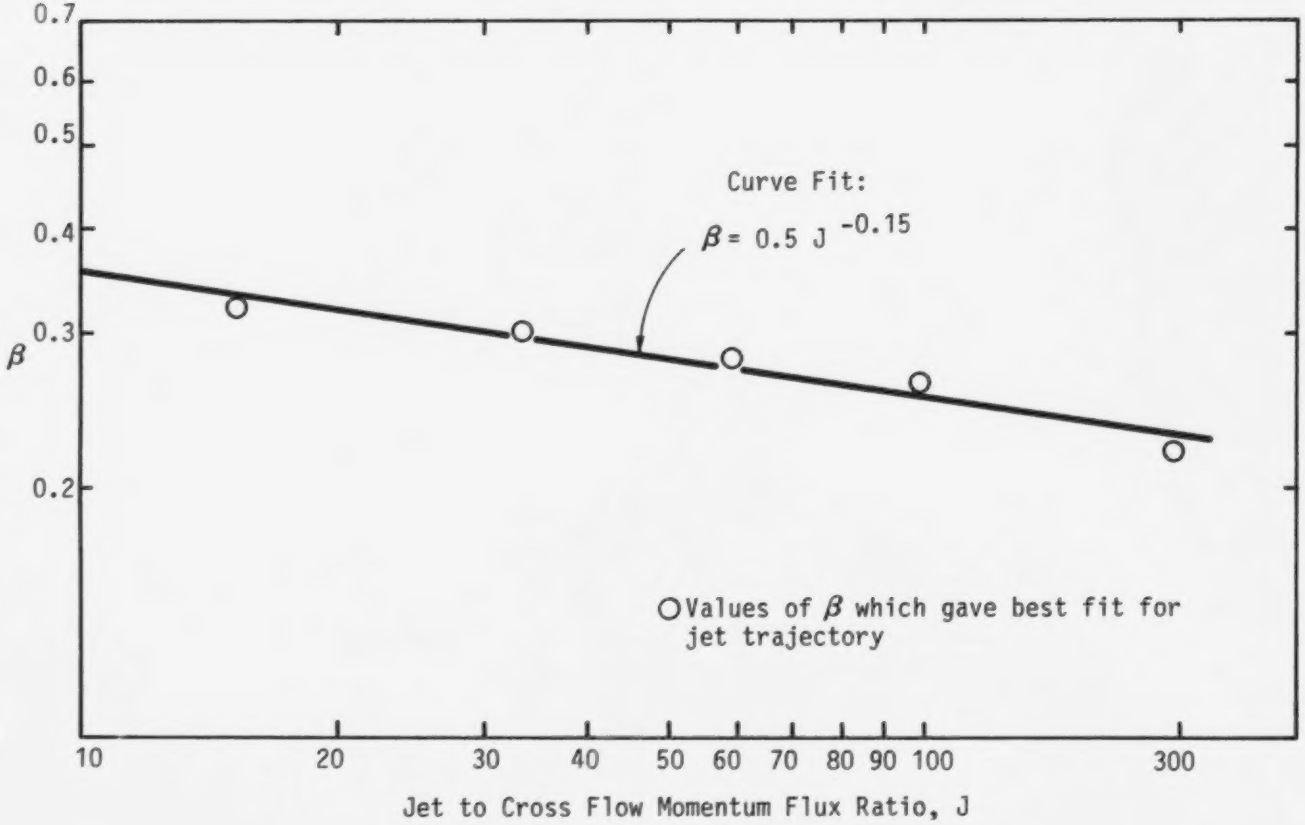


Figure 4-3. Determination of β function.

corresponding to the data of Kamotani & Greber (9) and Ivanov (10) were considered. The β function determined from this study was

$$\beta = 0.5\, J^{-0.15} \tag{4-23}$$

Jet trajectories were recalculated with this β function for the calibration cases as well as other cases with different J values. Comparison of calculated and experimentally determined jet trajectories is shown in Figure 4-4. The agreement between the calculated and the measured jet trajectories was good. The ability of the model to predict the jet trajectories over a wide range of momentum flux ratios was also demonstrated based on the results shown here. The trajectory comparisons were carried out for both isothermal and non-isothermal jets with jet to cross flow density ratios greater or less than one.

Because the calibration of entrainment rates was performed on the basis of matching the jet trajectories, it was desired to further verify the validity of the entrainment law by comparing a different jet parameter. This was achieved by comparing

- The jet fluid concentration decays along the jet trajectory for isothermal jets, $\bar{C}/C_0$
- The non-dimensional temperature excess decay along the jet trajectory for non-isothermal jets, $(\bar{T} - T_\infty)/(T_0 - T_\infty)$

For the first set, two experiments were carried out specifically to obtain a detailed characterization in the near field of these jets. These experiments were described in detail in Section 3.3.3. For non-isothermal jets, detailed measurements of Ivanov (10) were interpreted based on the assumption that the velocity and temperature profiles were self-similar Gaussian profiles. Although this is not strictly true for a jet in cross flow, the real profiles are approximately of Gaussian shape, especially in the downstream regions of the jet. Figure 4-5 summarizes the dilution profiles for five jets. The agreement between the measured and predicted

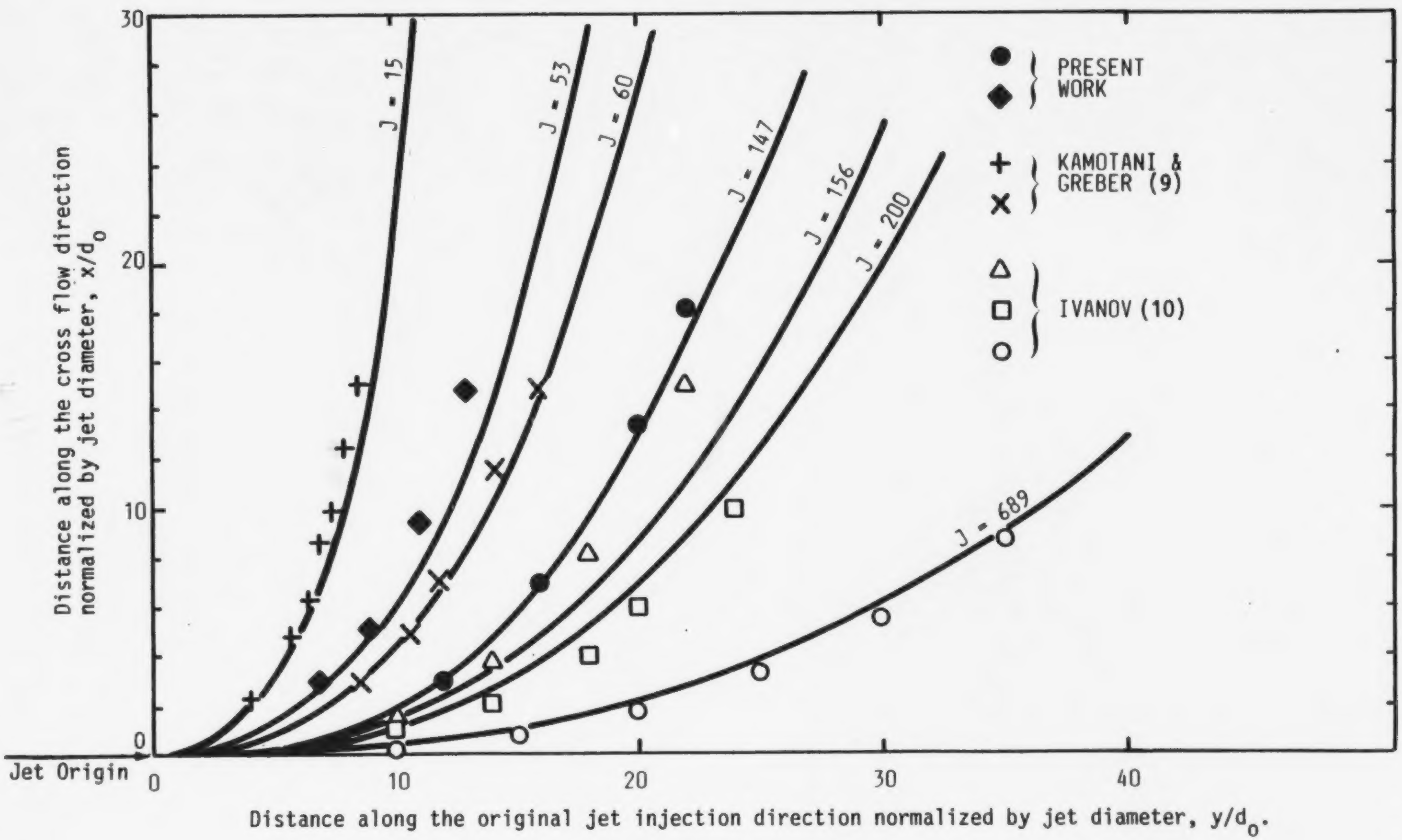


Figure 4-4. Comparison of measured (data points) and calculated (lines) jet trajectories at different J values. (See Figure 4-5 for further information on the experiments).

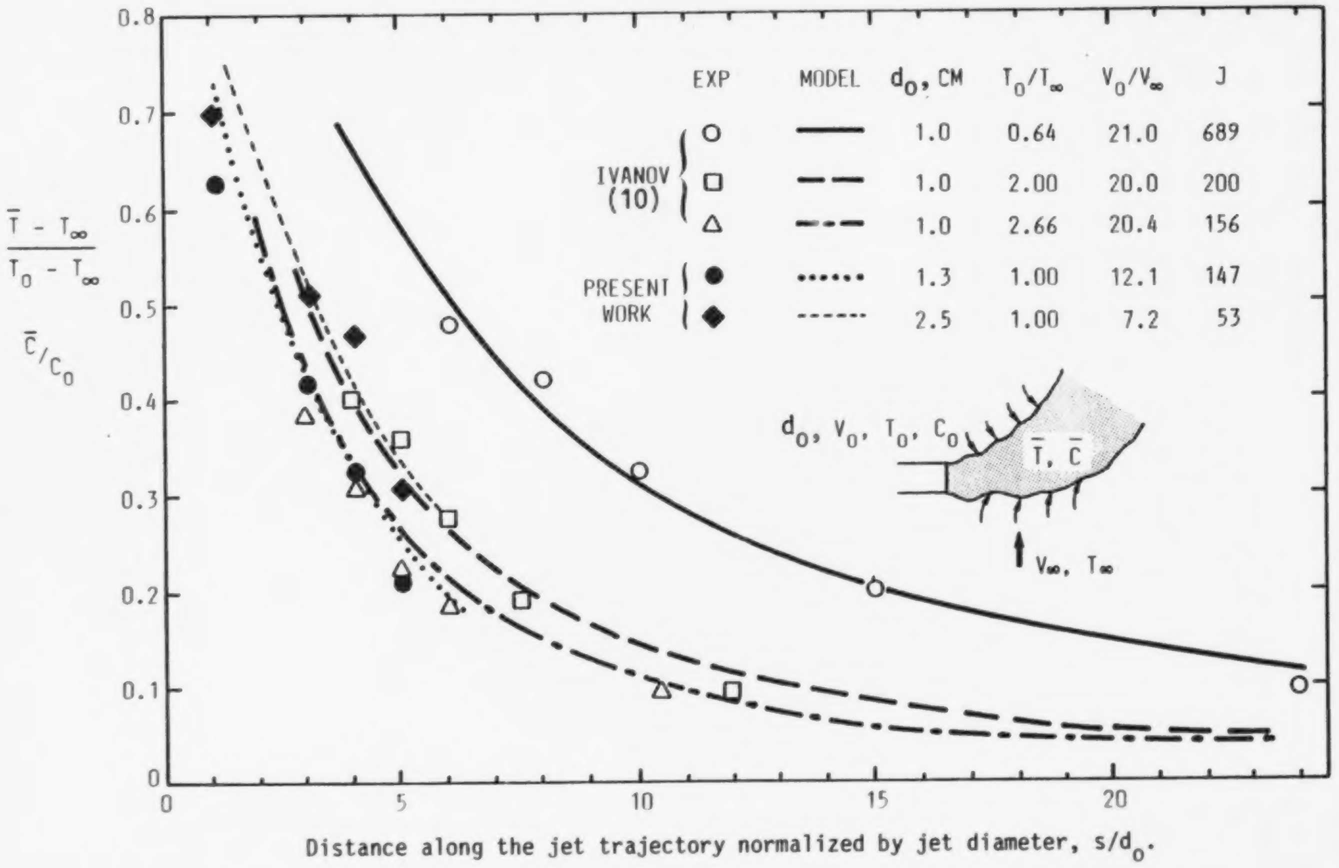


Figure 4-5. Comparison of dilution rates for isothermal and non-isothermal jets in uniform cross flow.

decay profiles was remarkable considering the simplified one-dimensional treatment of the jet. Especially, the experiments conducted to evaluate the dilution rates in the near field of the jet ($s/d_0 < 5$) were in good agreement with the predicted rates. The density effects were also correctly predicted by the model, indicating a slower decay of jet fluid concentration for a cold jet into a hot gas stream than that for an isothermal jet or a hot jet into a cold gas stream. This comparison further confirmed that this model can be used as a predictive design tool. The next step in the development of this model was to extend it to the complex flow field of a utility boiler upper furnace such as that shown in Figures 3-4, 3-5 and 3-6. The next subsection describes this approach.

4.4 Model Extension to Boiler Flows

The complex flow and temperature fields in a boiler upper furnace can be incorporated in the previously described model if it is assumed that the effect of the jet on the main flow field is negligible. This allows direct prescription of flow and temperature fields into the formulation in a convenient form so that the jet experiences these complex fields. The key differences in this case are:

- The furnace flow and temperature fields are functions of space variables (x and y). i.e. V_n (x,y), V_t (x,y) and T (x,y).

- The heat loss term, dq_L/ds is non-zero as a consequence of heat loss to the cold furnace walls.

The flow field prescription for a typical boiler upper furnace flow was given from the measured velocity profiles shown in Figures 3-4, 3-5 and 3-6. This involved dividing of the flow into a number of stream tubes, boundaries of which were calculated based on velocity measurements and streak photographs. The stream tubes were then assigned values of nondimensional stream function. The nondimensional stream function, ψ, values were interpolated and a numerical field representation of the stream function was prepared for a rectangular grid. These arrays were input into the computer program, thus allowing the model to make direct use of experimental data. This approach was selected in preference to a possible analytical description of the flow field or a complicated fluid dynamic flow code.

To describe the temperature field, it was found best to input a two-dimensional array of temperature values at points on a rectangular "grid" within the flow region of interest. The number of grid points in each direction (x and y), as well as one dimensional arrays describing the location of the grid points in each dimension were also input. The computer program allowed for multiplication of temperature and location arrays by a scale factor, and for translation of the location arrays, so that simple global changes may be made without tedious changes to large input arrays. The input temperature field was normalized to an array of, Q_∞, simply by dividing the temperature values by the initial jet temperature T_0 (see equation (4-9)). The program linearly interpolated between Q_∞ values at the four grid points immediately surrounding the point of interest to find Q_∞ at that point. Points outside the array were evaluated by extrapolation. However, this could lead to unrealistic values far from the array boundary. Hence, it was best to specify a temperature field surrounding the entire region of interest.

The calculation of velocity components used an array input similar to that of temperature. The velocity components were obtained from the input stream function array by:

$$V_x = \rho_0/\rho_\infty \; \partial\psi/\partial y \tag{4-24}$$

$$V_y = -\rho_0/\rho_\infty \; \partial\psi/\partial x \tag{4-25}$$

where ρ_0 is the reference (jet inlet) density and ρ_∞ is the crossflow density at the point of interest. One advantage of this type of input is that velocities calculated in this manner satisfy conservation of mass. Other additional information required to find absolute values of the stream function and the velocity magnitudes, are the total mass flow through the boiler, and the flow enclosure dimensions (duct depth and width).

To evaluate equations 4-24 and 4-25, the gradients were approximated by finite differences in stream function and coordinate values for two adjacent array points:

$$V_x \approx \rho_0/\rho_\infty \;\; \Delta\psi/\Delta y \tag{4-26}$$

$$V_y \approx -\rho_0/\rho_\infty \;\; \Delta\psi/\Delta y \tag{4-27}$$

In this formulation, the coordinate grid points used for stream function needed not be the same as those for temperature. However, the temperature values were interpolated to find ρ_∞ at the location where each velocity component was evaluated. To find the velocity components at a specific point within a stream function "grid cell", velocity components normal to each face of the grid cell were calculated using (equations 4-26 and 4-27), and then interpolated to the point of interest. From these velocity components, the velocity magnitude and direction were also calculated. Using jet angle, θ, this velocity resolved into its components V_t and V_n.

It should be noted that in a variable flow field there is an ambiguity in evaluating the value of momentum ratio J from which β is calculated (equation 4-23). In the results presented here, J was calculated using the density and velocity values at the jet inlet, since normal entrainment component is most significant near the base of the jet. As a check, several other calculations were made:

- using an average J for the entire flow field
- using local J values calculated along the jet trajectory

The effect of these variations in the evaluation of β was not significant.

The only remaining quantity to be determined is dq_L/ds, the rate of heat loss in the jet with respect to streamwise distance. Instead of undertaking a complicated analysis of heat transfer, it was assumed that a heat loss coefficient can be deduced from the rate of change of crossflow temperature. The rate of change of temperature for a pocket of gas in the crossflow is:

$$\frac{DT_\infty}{Dt} = V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} \qquad (4\text{-}28)$$

noting that the $T_\infty / t = 0$ since the temperature field is steady. The rate of heat loss per mass of fluid per time, is:

$$\frac{q_{L\infty}}{\dot{m}} = -C_{p_\infty} \frac{DT_\infty}{Dt} \qquad (4\text{-}29)$$

The heat transfer coefficient k is defined so that (equation 4-29) can be rewritten as:

$$\frac{q_{L\infty}}{\dot{m}} = k\ (T_\infty - T_W) \qquad (4\text{-}30)$$

where T_W is a reference wall temperature for the heat loss. It was assumed that k was the same for heat transfer from the furnace to the walls as for heat transfer from the jet to the walls. Using equations 4-29 and 4-30 to solve for k in terms of known quantities, and substituting into a similar equation for heat loss from the jet:

$$q_{L\infty} = \dot{m}_j \left(-C_{p_\infty} \frac{DT_\infty}{Dt}\right) \frac{(T_j - T_W)}{(T_\infty - T_W)} \qquad (4\text{-}31)$$

Considering a section of jet which is, ds, thick in the streamwise direction,

$$d\dot{m}_j = \rho_j\ \pi\ b^2\ ds \qquad (4\text{-}32)$$

Therefore the rate of change of q_L per streamwise distance s, is:

$$\frac{dq_L}{ds} = -\ \rho_j b^2\ C_{p_\infty} \frac{DT_\infty}{Dt} \frac{(T_j - T_W)}{(T_\infty - T_W)} \qquad (4\text{-}33)$$

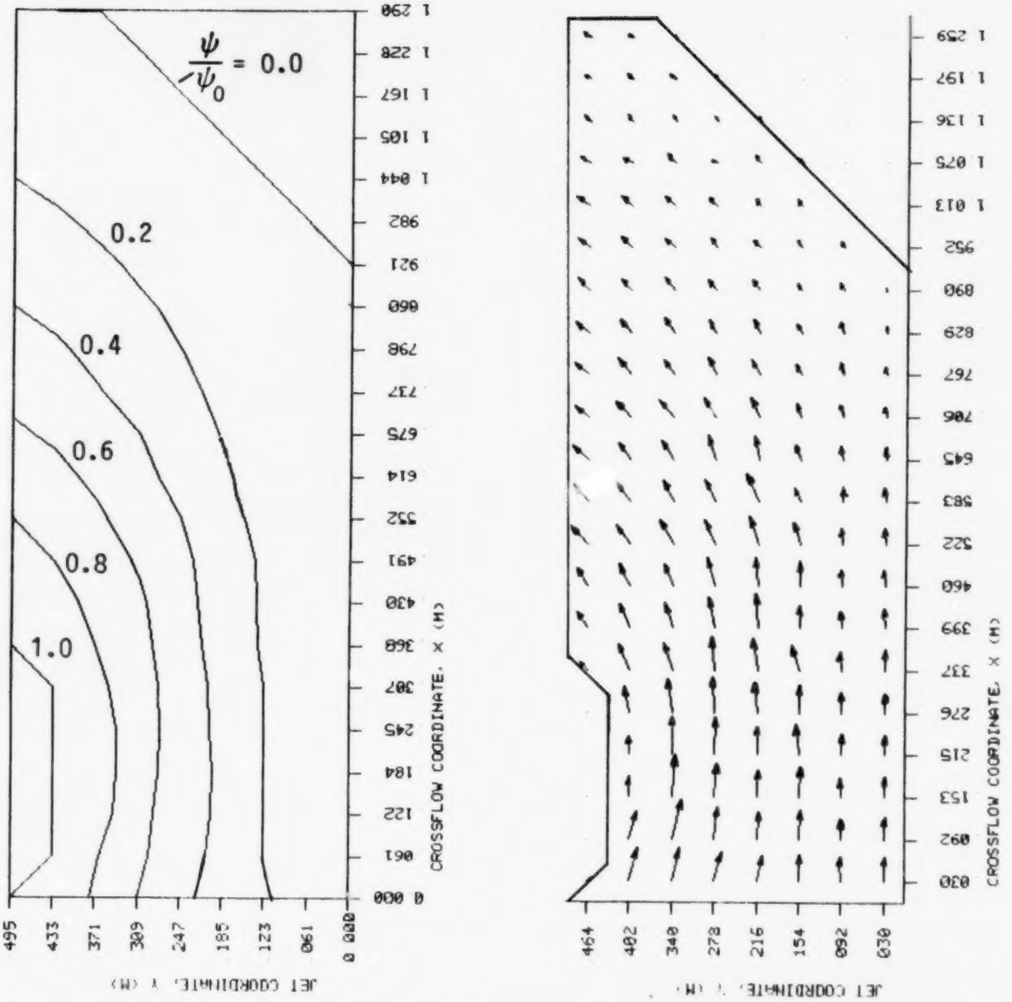
This expression may be substituted in equation 4-13. The only new input quantity is the wall temperature T_w. The analysis presented here is a very simple heat loss analysis, but it does give the desired limiting behavior that as T_j approaches T_∞ , the heat loss rate of the jet approaches that of the crossflow gas.

An updated version of the computer code was written and tested systematically against earlier results to ensure that the model formulation was correct. This code was then applied to the prediction of trajectory and spread of a jet in an isothermal scale model of the Edgewater boiler. Streamlines and relative velocity vectors for this flow field are shown in Figure 4-6.

Figure 4-7 shows the comparison of jet model predictions (centerline trajectory and spread) with a time exposure photograph of smoke injected into a 0.59 cm diameter jet at a momentum flux ratio of 50. The jet trajectories match reasonably well except near the top wall, where the jet model predictions nonchalantly goes through the roof. This is due to the omission of the wall effects. While this invalidates results in a region where a jet is impinging near a wall, the results are believed to be valid in the first 20-30 jet diameters where the time-dependent behavior of calcination and sulfation processes are most important.

4.5 Model Application Examples

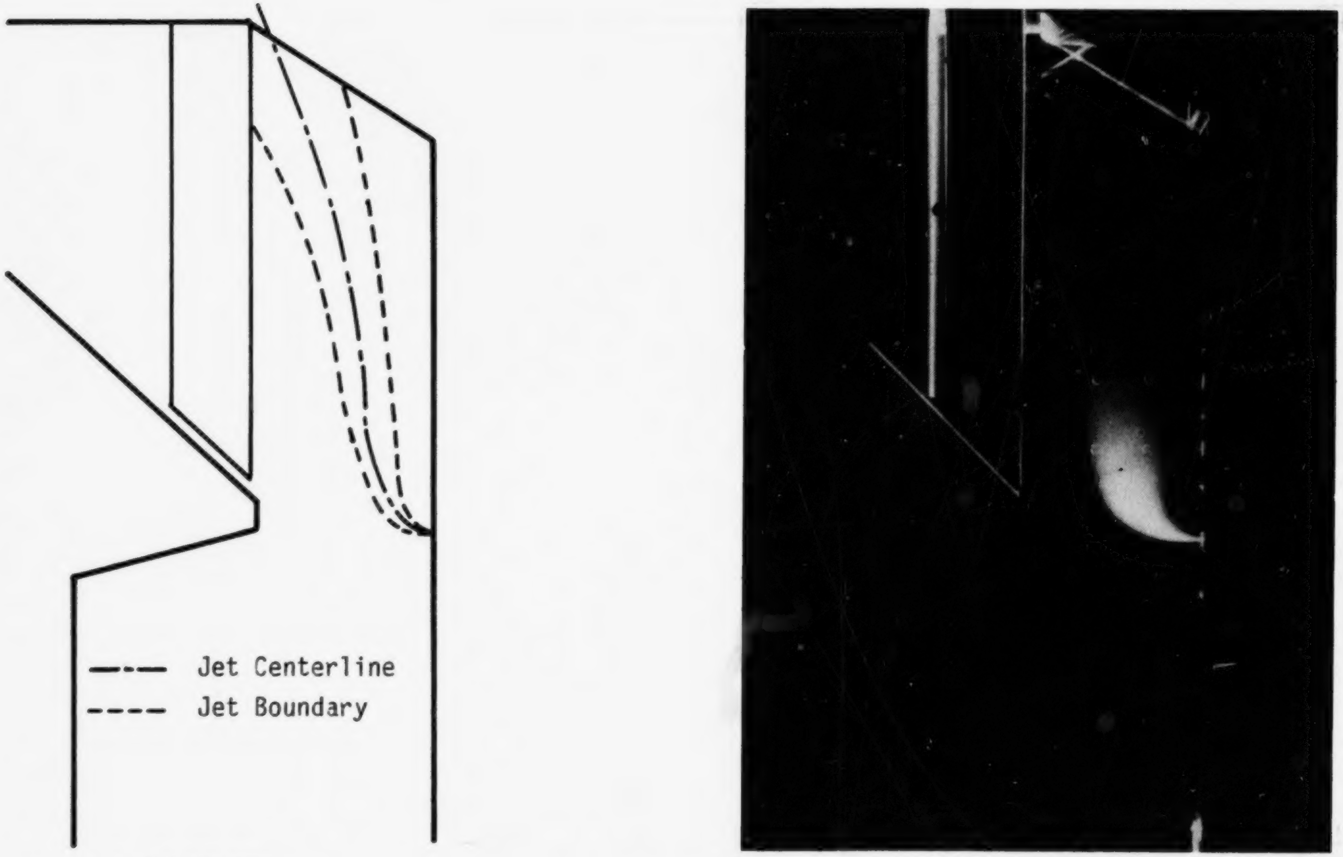
The application of the model described in this section lies in predicting the temperature-time and concentration-time profiles of a jet injected in a cross-flow stream. This provides the input conditions for a time dependent calcination/sulfation model to predict cumulative sulfur capture with time. The calcination/sulfation model has been described in reference (3). The schematic of this approach is outlined in Figure 4-8. The upper furnace temperature and velocity fields are input into the jet model which predicts the bulk temperature-time and concentration-time profiles in the injection jets. Although it can be envisioned that a multitude of temperature and concentration-time profiles exist in a jet due



Nondimensional Stream Function

Velocity Field

Figure 4-6. Streamlines and velocity field generated for the Edgewater flow field which was used in calculation of results in Figure 4-7.


Jet Centerline
Jet Boundary

(a) CALCULATED

(b) OBSERVED

Figure 4-7. Computer jet trajectory and spread (a) and the observed smoke trace of a jet (b). Jet diameter = 0.59 cm. Jet to Cross Flow Momentum Flux Ratio, J = 50.

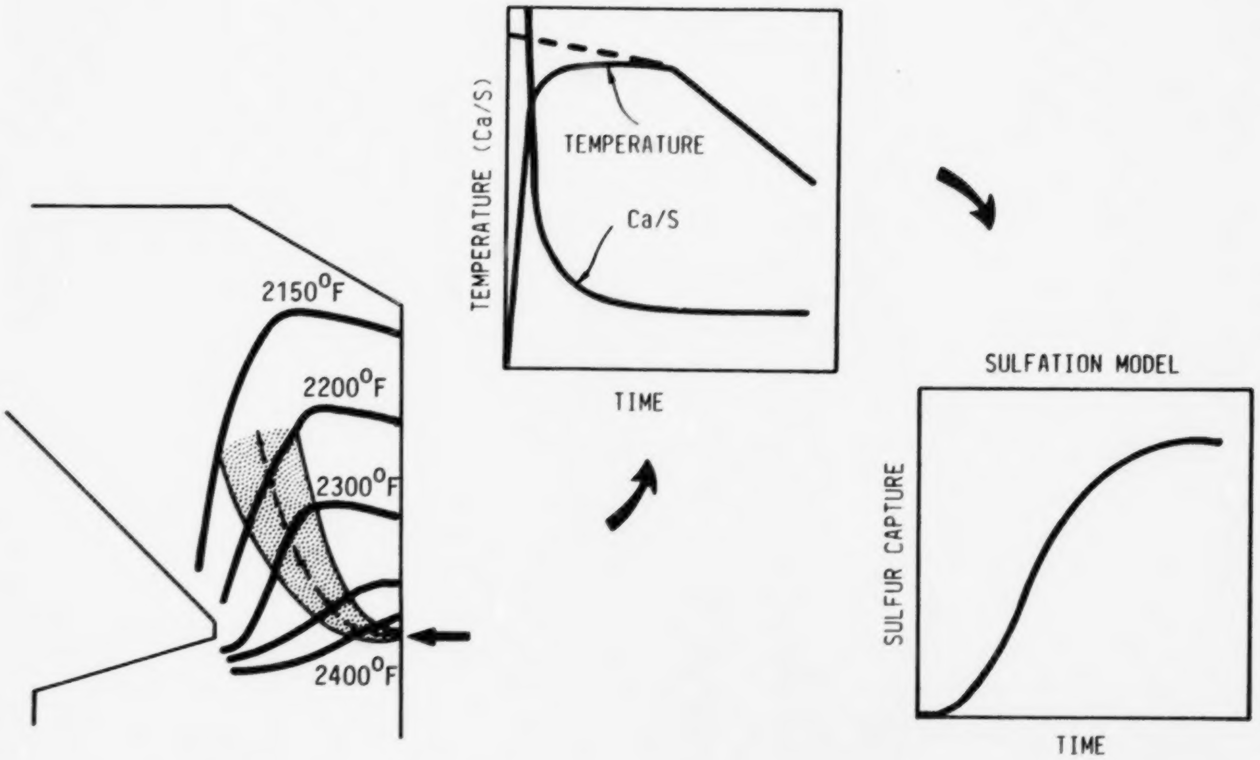

2150°F
2200°F
2300°F
2400°F
TEMPERATURE (Ca/S)
TEMPERATURE
Ca/S
TIME
SULFATION MODEL
SULFUR CAPTURE
TIME

Figure 4-8. Predictive scheme to determine the progress of sulfation in sorbent injection jets.

to the variations across the jet (i.e. edges of the jet heat up considerably faster than the center), it is believed that the computed profiles represent a bulk average with a reasonable time resolution. The temperature and concentration variations can then be used as input parameters in the calcination/sulfation model to predict the progress of sulfation. Figure 4-9 gives an example of this for a particular injection test carried out in a tower furnace described in the next section. It can be noted that the initial heat-up of the jet was confined to the first 200 milliseconds in the same region where the Ca/S ratio in the jet was declining rapidly. In this case, the sulfur capture leveled off at about 0.7 seconds after which the increase in capture was incremental. The final value of the sulfur capture compared favorably with the range of the experimentally measured values as shown on the right-hand side of this figure. Other examples of the model application will be given in the following two sections.

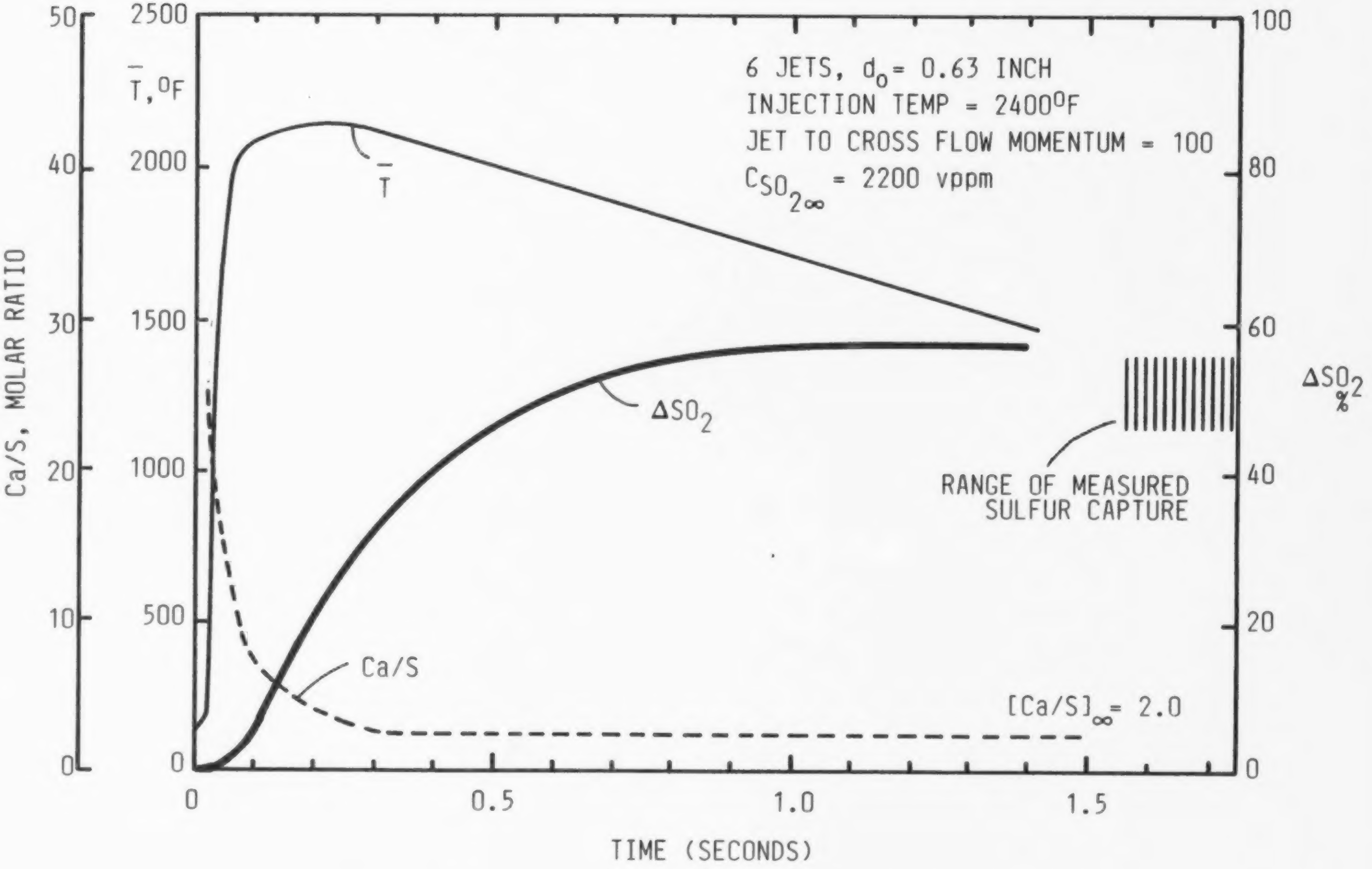


Figure 4-9. Computed progress of sulfur capture based on jet and calcination/sulfation models.

5.0 COMBUSTION TESTS IN A TOWER FURNACE

A series of sorbent injection tests were conducted in a modified pilot scale combustor to determine the impact of sorbent injection parameters on the sulfur capture efficiency. These parameters were those which had the largest impact on mixing and dispersion based on isothermal studies. The three key parameters identified were

- Jet velocity or momentum
- Number of injection jets
- Location of injection jets

The experiment was designed to be a close simulation of thermal and flow conditions encountered in full scale utility boiler furnaces. In the following subsections, the experimental systems are first described in Section 5.1. This is followed by the thermal environment characterization and test matrices in Section 5.2 and 5.3. In Section 5.4, the experimental results are presented. Detailed characterization of mixing from tracer concentration measurements is discussed in Section 5.5. The test results are interpreted with the isothermal tests and computational models in Section 5.6.

5.1 Experimental Systems

5.1.1 Test Furnace Design

The design of the test chamber for the experiments was based on simulation of the Edgewater boiler upper furnace. The transition section of the reburning tower furnace, shown in Figure 5-1, was modified to resemble an inverted model of the Edgewater boiler upper furnace. This section was constructed to be similar to the full-scale boiler with regard to:

- Geometry
- Gas flow patterns

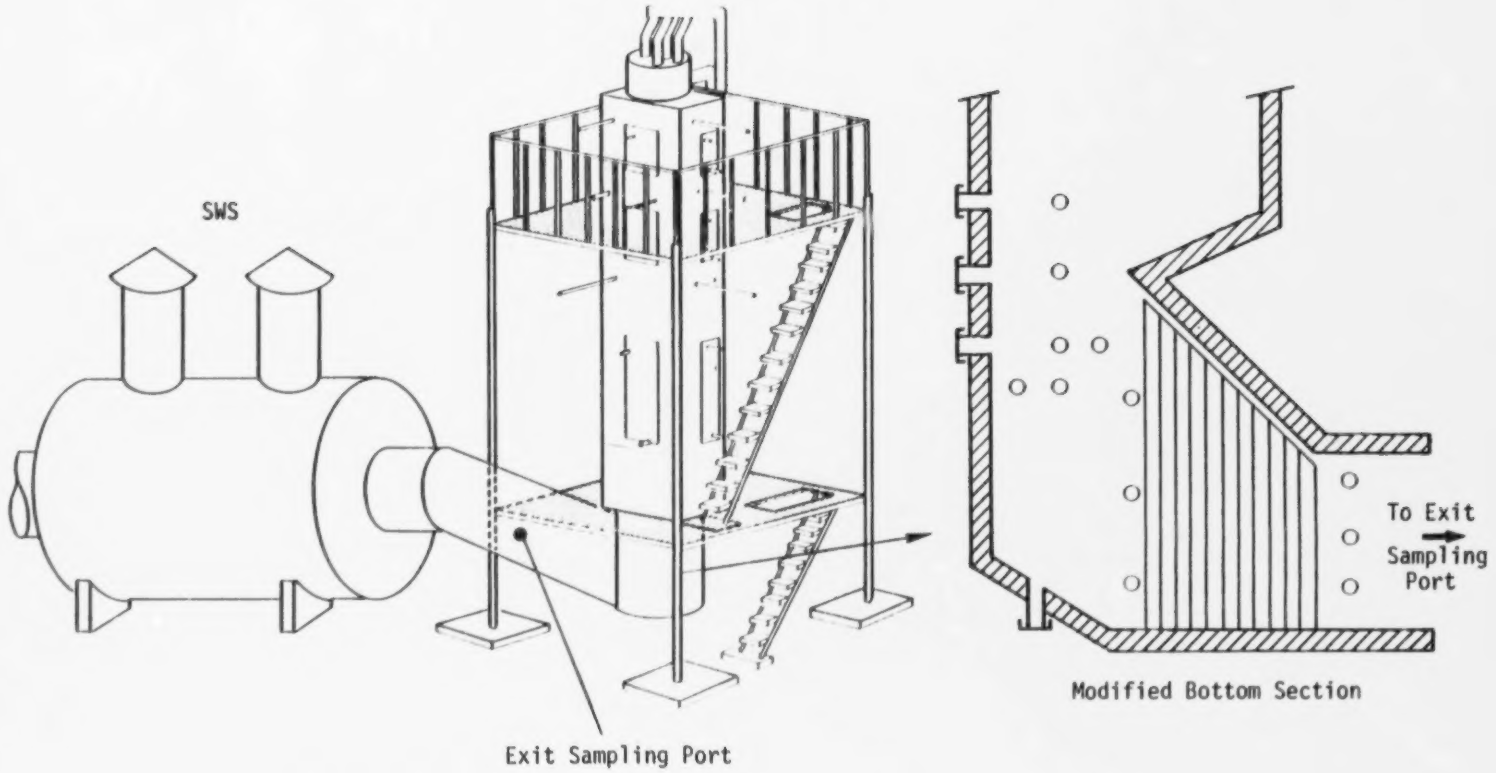

SWS
Exit Sampling Port
Modified Bottom Section
To Exit
Sampling
Port

Figure 5-1. Reburning tower furnace and modified section.

- Spatial gas temperature distribution and temperature history along the flow path (i.e. quench rates in the sulfation temperature window).

The duct shape and channeling of flow by superheater tube banks were simulated in a 1/5.6 geometric scale model. With this scale factor, the modeled furnace width corresponded to 3/4 width of the full-scale boiler. Figure 5-2 shows the modified section with its dimension.

Similarity of gas flow patterns was assured by similar geometry and the adequate Reynolds number of the bulk flow. Matching of temperatures and residence times in the model with those in the Edgewater boiler was attempted by

- Operating the reburning tower furnace at a throughput that gives equality of residence times.

- Adjusting the tower furnace height (by removing furnace sections) to match the bulk gas temperature at the nose plane to be around 1300°C (1300°C corresponded to the bulk average gas temperature at the nose plane at full load in Edgewater boiler).

- Removal of heat from the flue gas by water-cooled tubes simulating the radiant superheaters to give the same quench rate of flue gas as in the full-scale unit.

Model was constructed from steel and lined inside with a 7.6 cm (3.0 inch) thick layer of refractory. A cutaway view of the test section is shown in Figure 5-3. A number of sampling ports and sorbent injection ports were installed to allow sampling and sorbent injection at various locations. Sorbents could be injected at three elevations with 3, 6, and 9 injectors on the front wall. The ports on the side walls were designed to facilitate sampling and sorbent injection through side walls. Injection ports were also incorporated for roof injection.

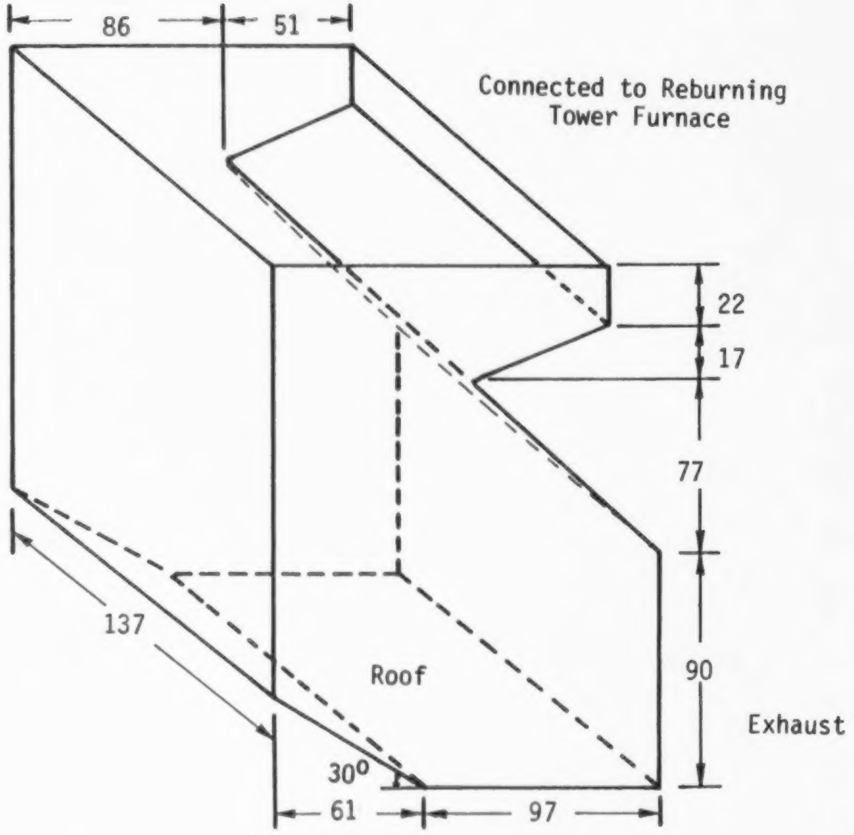

86
51
Connected to Reburning
Tower Furnace
22
17
77
90
Exhaust
137
Roof
30°
61
97

Figure 5-2. Edgewater upper furnace model isometric sketch. (All dimensions are the outside dimensions in cm., inside covered with a 7.6 cm thick layer of refractory).

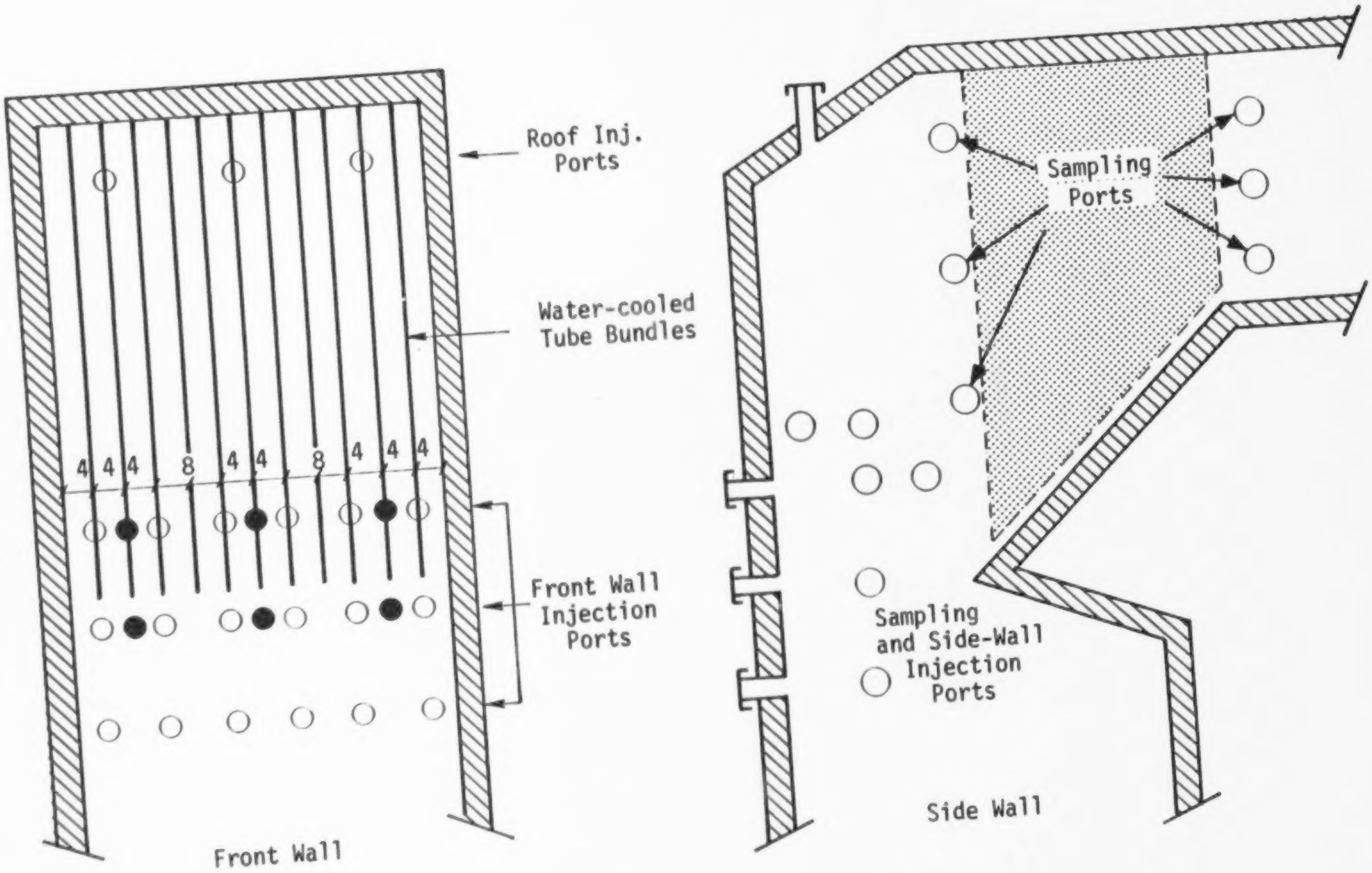

Roof Inj. Ports
Water-cooled Tube Bundles
4
4
4
8
4
4
8
4
4
4
Front Wall Injection Ports
Front Wall
Sampling Ports
Sampling and Side-Wall Injection Ports
Side Wall

Figure 5-3. Cutaway view of test section.

Table 5-1 lists the furnace operating parameters and the coal fired during testing. Pittsburgh #8 coal, which is fired in the Edgewater boiler, was used during this test. In order to match the residence times in the model and the prototype, furnace was operated at 4.2 x 10^6 Btu/hr with 20 percent excess air. Based on the results of a heat transfer analysis, the top three sections of the reburning tower furnace were removed to obtain an average gas temperature of 1300°C at the nose plane. The Reynolds number based on hydraulic diameter at the nose plane was adequate to ensure turbulent flow.

5.1.2 Systems

The experiments were carried out in a modified section of the reburning tower furnace as described before. The reburning tower furnace itself is a down-fired, refractory lined furnace with a 1.2 m. square inner cross section as shown in Figure 5-4. The furnace height was 5.0 m. from the burner plate down to the test section. The combustion products generated by coal combustion flowed downward before entering the test section. Heat was removed from the gas stream with cooling coils arranged to simulate the high temperature superheater section of the Edgewater boiler. Sorbent injection was performed with various injector configurations on the walls of the test section.

The general arrangement of the fuel and air delivery, and exhaust systems is shown in Figure 5-5. Reburning tower furnace utilizes the fuel, air delivery and exhaust systems of the Small Watertube Simulator (SWS) furnace. Coal feed system consists of a twin screw coal feeder which is supplied by pulverized coal from a hopper. Coal is transported into the four burners with transport air supplied by a compressor and a booster fan.

Preheated combustion air is metered with venturi flow meters and supplied to the secondary passage of the coal burners. Coal burners were single secondary passage swirl burners as shown in Figure 5-6. The four burners were arranged concentrically at the furnace top. Cooling for the reburning tower furnace, for the simulated superheater cooling coils, and the

TABLE 5-1. FURNACE OPERATING CONDITIONS

Parameter	Value
Fuel	Pittsburgh #8 Hi. Vol. Bituminous Coal
Furnace Load	1.23 MW_{th}
Excess Air	20% TA
Average Gas Temperature Entering Nose Plane	1300°C
Average Gas Velocity Entering Nose Plane	3.0 m/s
Reynolds No. at Nose based on Hydraulic Diameter, Re_{D_H}	10,700

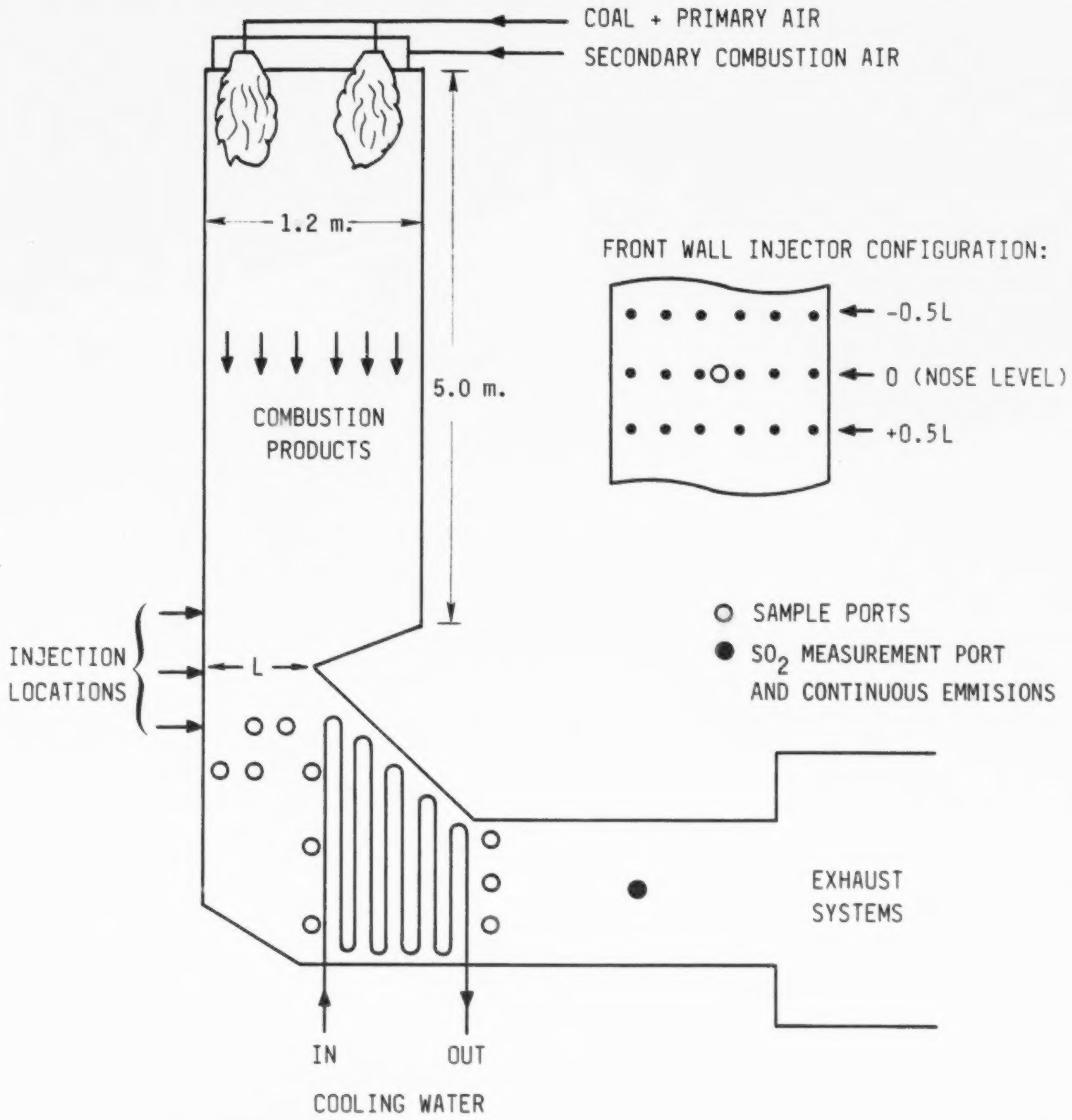

COAL + PRIMARY AIR
SECONDARY COMBUSTION AIR
1.2 m.
5.0 m.
COMBUSTION PRODUCTS
FRONT WALL INJECTOR CONFIGURATION:
-0.5L
0 (NOSE LEVEL)
+0.5L
INJECTION LOCATIONS
L
○ SAMPLE PORTS
● SO_2 MEASUREMENT PORT AND CONTINUOUS EMMISIONS
EXHAUST SYSTEMS
IN
OUT
COOLING WATER

Figure 5-4. Schematic of tower furnace and the modified experimental section.

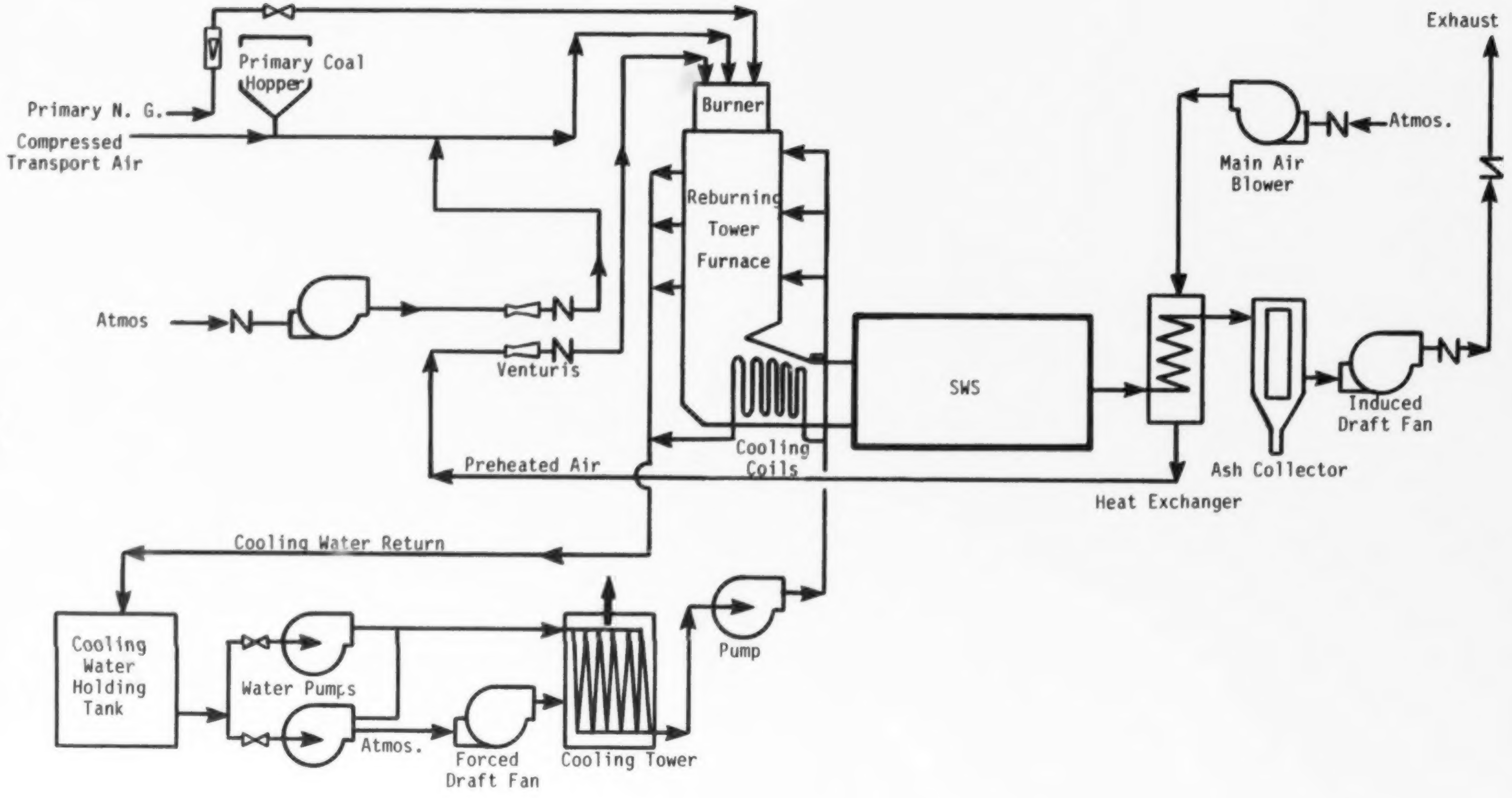
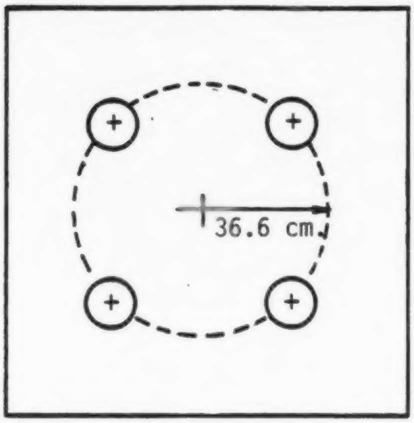

Primary N. G.
Primary Coal Hopper
Compressed Transport Air
Burner
Reburning Tower Furnace
Atmos
Venturis
Cooling Coils
SWS
Preheated Air
Main Air Blower
Atmos.
Exhaust
Heat Exchanger
Ash Collector
Induced Draft Fan
Cooling Water Return
Cooling Water Holding Tank
Water Pumps
Atmos.
Forced Draft Fan
Cooling Tower
Pump

Figure 5-5. System schematic of experimental facility.

- Nozzle Layout



- Nozzle Schematic

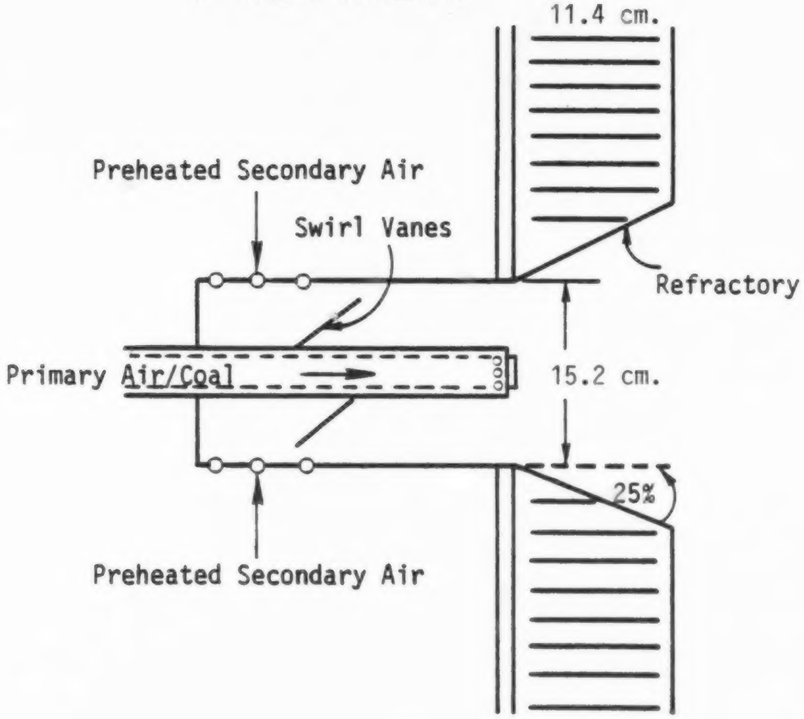

11.4 cm.
Preheated Secondary Air
Swirl Vanes
Refractory
Primary Air/Coal
15.2 cm.
25%
Preheated Secondary Air

Figure 5-6. Main burner injection scheme.

SWS furnace was provided with a closed-loop water cooling circuit shown in Figure 5-5. Existing exhaust systems of the SWS furnace were utilized for particulate control before the flue gas stream was emitted into the atmosphere.

5.1.3 Fuels and Sorbents

During the tests, natural gas and Pittsburgh #8 high-volatile bituminous coal were fired in the furnace. Natural gas was used for preheating the furnace and during the gas dispersion tests. Natural gas was taken from the Southern California Gas company mains without processing. The principal constituents with their mole fractions were methane 0.928, ethane 0.036, propane 0.009 and nitrogen 0.014. The lower heating value was about 47.5 MJ/kg and density is about 0.72 kg/m^3 at 20^{o}C and one atmosphere.

The coal fired during the tests was a high volatile bituminous Pittsburgh #8 coal. This coal was selected as the test fuel since it was the same fuel supplied to the Edgewater Power Station which is the site of the LIMB demonstration project. This coal was also desirable as a test fuel because of its high sulfur content. During the tests, coal samples were obtained daily and selected coal samples were analyzed subsequently. Table 5-2 shows the analyses of three samples spanning the test period between 10/18/85 and 12/06/85. The variations in all constituents were less than 17 percent for the three in-house coal analyses. A comparison of the in-house and an external lab analysis of the same sample is also shown in this table. Variations in major constituents were less than 5 percent. The coal size distributions are shown in Figure 5-7. Typically, the coal fineness was between 60 to 70 percent by weight less than 74 microns (200 mesh).

Linwood atmospheric hydrate was selected as the base sorbent during these tests. Recent experimental results with $Ca(OH)_2$ indicated that hydrates have a higher potential for sulfur capture than carbonates based on the high calcium utilizations obtained with these materials. Furthermore, recent tests at EER showed that Linwood performance was better than other

TABLE 5-2. COAL ANALYSES

Sample Date Analysis		10-30-85*	11-8-85*	11-20-85*	11-20-85**
Proximate Analysis (Percent, Dry)					
Ash		12.50	13.29	11.86	12.44
Volatile Matter		34.51	35.62	37.90	36.17
Fixed Carbon		52.99	51.09	50.24	51.39
Moisture (As Received)		1.44	1.35	1.33	2.03
Ultimate Analysis (Percent, Dry)					
C		70.26	68.49	70.15	71.52
H		4.66	4.51	4.77	4.81
N		1.25	1.46	1.32	1.34
S		2.98	3.04	3.31	3.23
Ash		12.50	13.29	11.86	12.44
O		8.35	9.21	8.59	6.66
Higher Heating Value, MJ/kg		-	-	-	29.63
Fusion Temp. (°C)	Oxid.	-	-	-	1467
	Redu.				1446

*EER Lab. Analysis
**Hazen Research Analysis

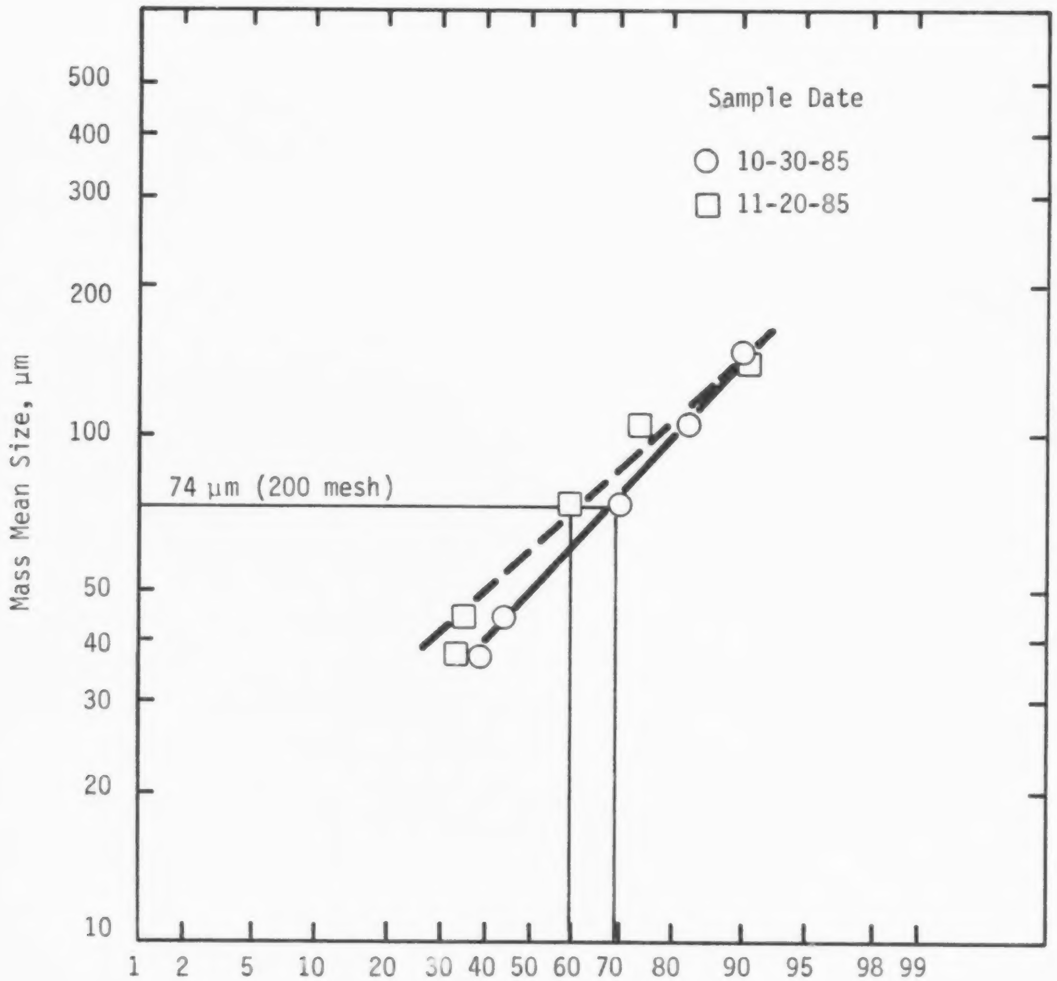


Figure 5-7. Coal size distributions.

hydrates and it showed the least batch to batch variation in its physical and chemical characteristics. Hence, it was chosen as the base sorbent. In addition, a few tests were conducted with Vicron 45-3, a $CaCO_3$ and Marblehead atmospheric hydrate, another commercial $Ca(OH)_2$. Table 5-3 lists the physical characteristics and chemical compositions of these materials. Figure 5-8 shows the size distributions of the powders obtained by sedigraph. Linwood particles were finer than the Marblehead particles followed by Vicron 45-3 being the coarsest among the three sorbents. The 50 percent mass mean equivalent diameters were 2 microns, 4 microns and 10 microns for Linwood, Marblehead and Vicron 45-3 respectively.

5.1.4 Measurements and Measurement Methods

5.1.4.1 Gas Sampling System

In all tests, the composition of the flue gas was monitored by continuous monitor type analyzers for O_2, CO, CO_2, NO_x and SO_2. The details of analytical systems and measurement methods as well as precision and accuracy tests are described in the Quality Assurance/Quality Control Activity Appendix A. Gas sample was continuously extracted from the exit location, shown in Figure 5-4, with a stainless steel water-cooled probe. The sample was treated by passing it through condensers and filters before being sent to the continuous monitors as shown in Figure 5-9. A separate phase-discrimination probe was used to make gas phase SO_2 measurements to minimize the reaction between the active particulates and the SO_2. However, the SO_2 tracer measurements while firing with natural gas were made with a standard water-cooled sampling probe since there was no active particulate in the system.

5.1.4.2 Temperature Measurements

Gas temperature measurements were made with water-cooled single radiation shield suction pyrometers. During the experiments, the temperature at the center of the nose plane was continuously monitored with a suction pyrometer. In addition, several complete surveys of temperature field were

TABLE 5-3. SORBENT CHARACTERISTICS

Characteristics	Sorbents	Linwood Atmospheric Hydrate ($Ca(OH)_2$)	Marblehead Atmospheric Hydrate ($Ca(OH)_2$)	Vicron ($CaCO_3$)
Physical Properties	Mean Size (μm)	2.2	4.3	9.8
	Pore Volume (cm^3/gm)	0.89	-	-
	Density (gm/cm^3)	2.30	2.26	2.71
	Surface Area (m^2/gm)	14.0	13.13	~2
Chemical Analysis (Percent by Wt)	Ca	51.6	52.2	39.2
	Mg	0.97	0.64	0.33
	Na	0.004	0.01	0.007
	Si	0.66	0.47	0.09
	Al	0.18	0.15	0.02
	Fe	0.27	0.38	0.06
	C	0.33	0.69	11.90
	H	2.48	2.32	0.08
	N	0.04	0.07	-
	S	0.00	0.06	0.01

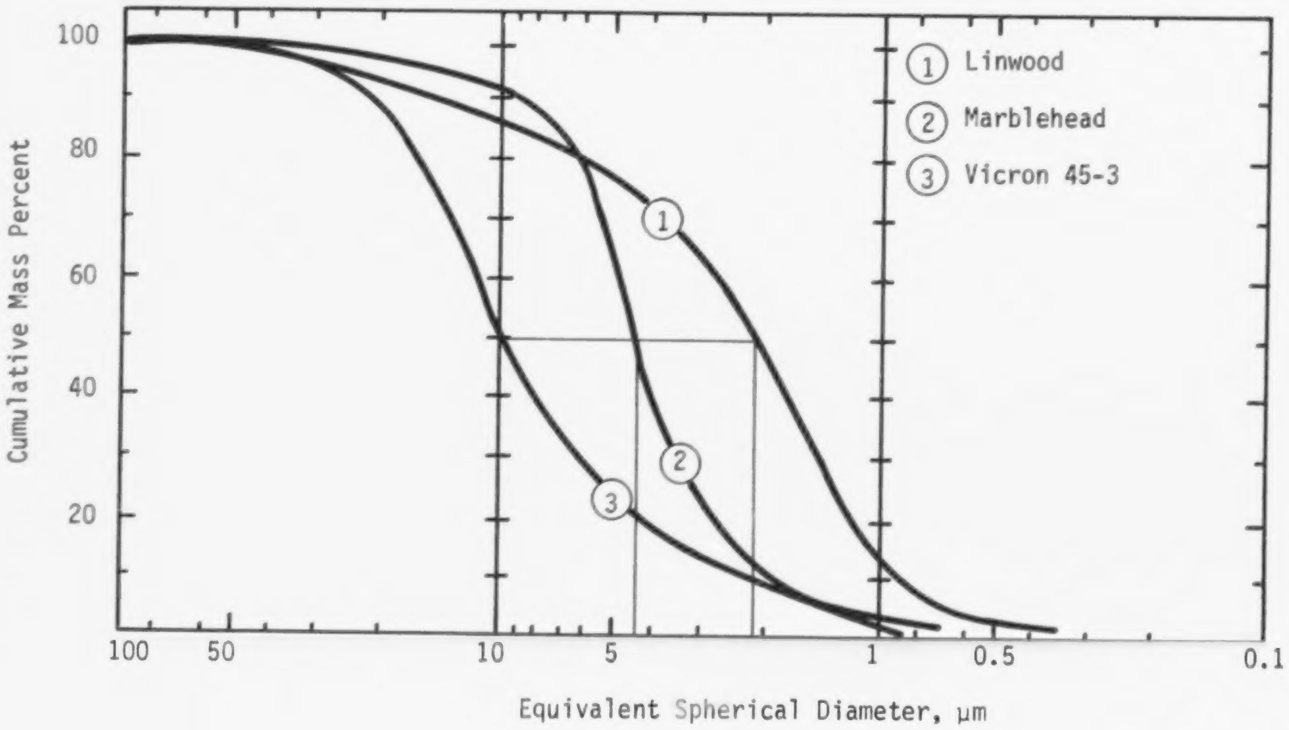


Figure 5-8. Particle size distributions of sorbents used during the tests.

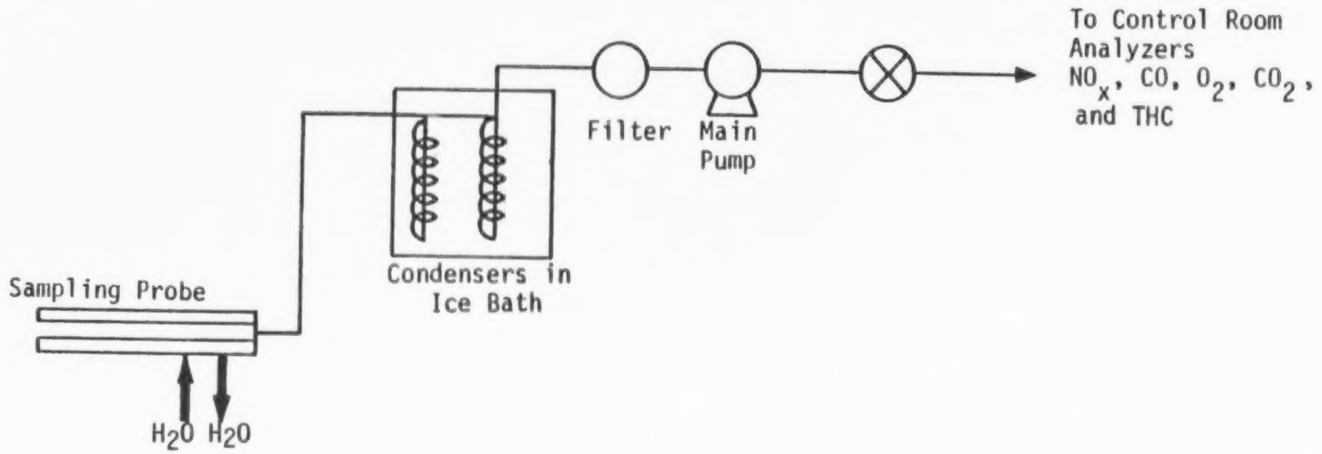

To Control Room
Analyzers
NO_x, CO, O_2, CO_2,
and THC
Filter
Main
Pump
Condensers in
Ice Bath
Sampling Probe
H_2O
H_2O

Figure 5-9. Continuous monitoring sampling system.

performed during the testing period. Bare thermocouples and thermocouples imbedded into the refractory walls were also used to monitor wall temperatures and gas temperatures. S and K-type thermocouples were used as appropriate.

5.1.4.3 Fuel and Sorbent Feed Rates

Natural gas flow rate was measured with a calibrated rotameter. Coal flow rate was measured with a manufacturer calibrated twin-screw volumetric feeder. This was double-checked with the feed rates calculated from coal composition, heating value, combustion air flow rates and the exhaust O_2 levels. Sorbent feed was measured with a single screw volumetric feeder calibrated before and after testing for a particular material. Feed rates were double-checked by measuring the differential weight loss during the measured time of the injection test.

5.1.4.4 Sorbent Carrier Air Flow Rate

Carrier air flow was measured with a calibrated venturi and orifice flowmeters. Figure 5-10 shows the sorbent feed system employed during these tests. Sorbent feed was picked up with compressed air through an ejector and transported to a 6 or 3-way symmetric splitter which was connected to the sorbent injectors. The splitter performance was tested several times during the tests. It was concluded that the sorbent was distributed uniformly among the split streams.

5.1.4.5 Solids Sampling

Samples of fly ash as well as fly ash/sorbent mixtures were taken at the exit sampling port with the system shown in Figure 5-11. A standard pyrex probe was used for collecting samples. Separation of the particulates from the gas stream was achieved by a glass cyclone.

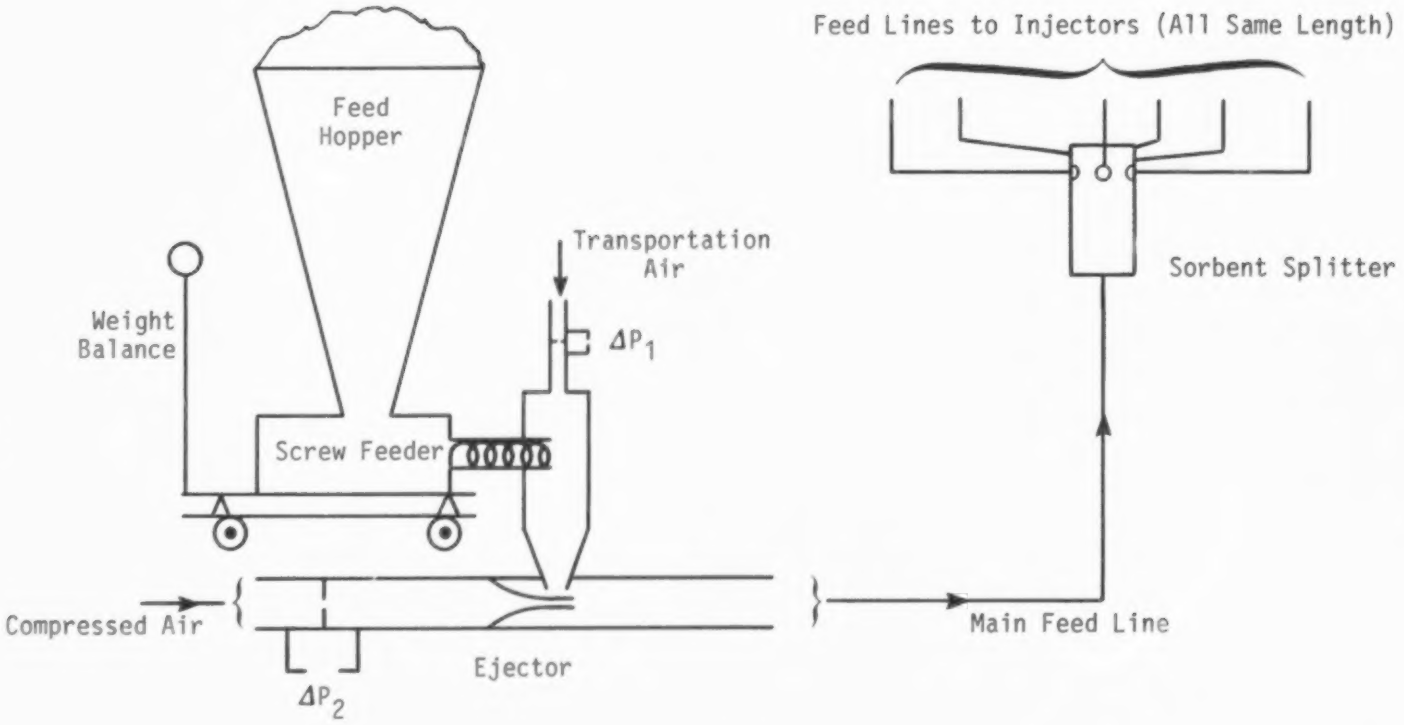

Feed Hopper
Weight Balance
Screw Feeder
Transportation Air
ΔP_1
Compressed Air
ΔP_2
Ejector
Main Feed Line
Feed Lines to Injectors (All Same Length)
Sorbent Splitter

Figure 5-10. Sorbent feed system.

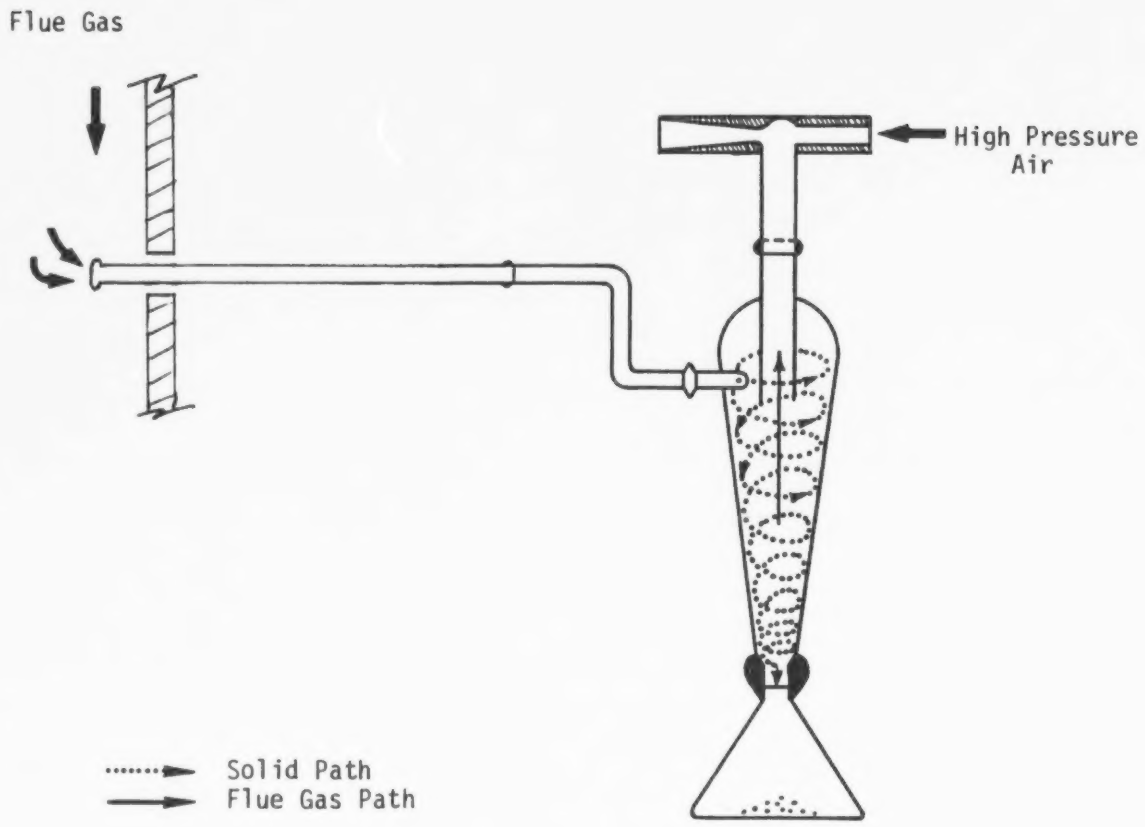

Flue Gas
High Pressure Air
Solid Path
Flue Gas Path

Figure 5-11. Solids sampling system.

5.1.4.6 Data Acquisition System

Data were obtained with the use of a continuous on-line computer and real-time data acquisition program. The program received input data every 35 seconds from each of the continuous gas monitors and from the pressure transducers and K-type thermocouples on all furnace input streams. With this information, the computer calculated firing rates, stoichiometries, air and flue gas flow rates, and gas species concentrations. Information was displayed on the computer screen and a printer. The data acquisition program was prepared for interactive use to set up a particular experiment or change input variables.

5.2 Thermal Environment Characterization

Before the beginning of the sorbent injection tests, the thermal environment in the test section was surveyed by conducting temperature measurements with water-cooled suction pyrometers. The furnace was operated at 1.41 MW_{th} (4.5 x 10^6 Btu/hr) with 22 percent excess air. Temperature measurements were made at three planes: horizontal nose plane and two vertical planes before and after the cooling coils as shown in Figure 5-12. At all measurement planes, the temperature variations in both directions were small. The average temperatures (as obtained by simple arithmetic averaging) were 1231°C, 1031°C and 854°C at the nose plane and the following two vertical planes downstream. Based on these bulk temperatures and the flowrates, the average gas residence times were calculated. The results of these calculations are shown in Figure 5-13 displaying the overall temperature-time relationship in the test section. Temperature profiles measured on different test days were used to calculate these quench rates. The results were repeatable. Also shown on this figure is the typical quench rate of an American boiler in the sulfation window. The gas quench rate in the sulfation window was representative of the boiler quench rates.

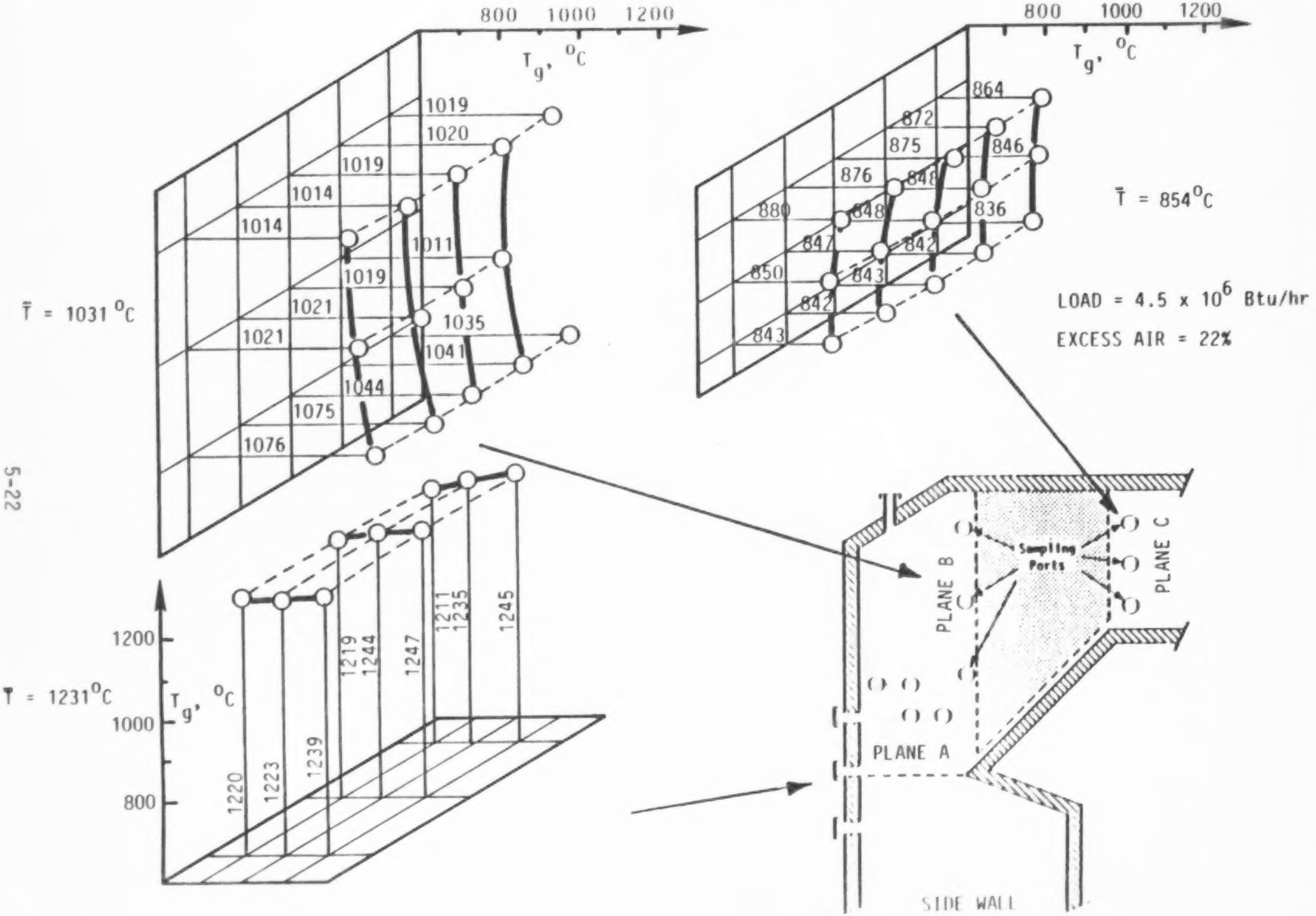


Figure 5-12. Measured temperature profiles in the test section.

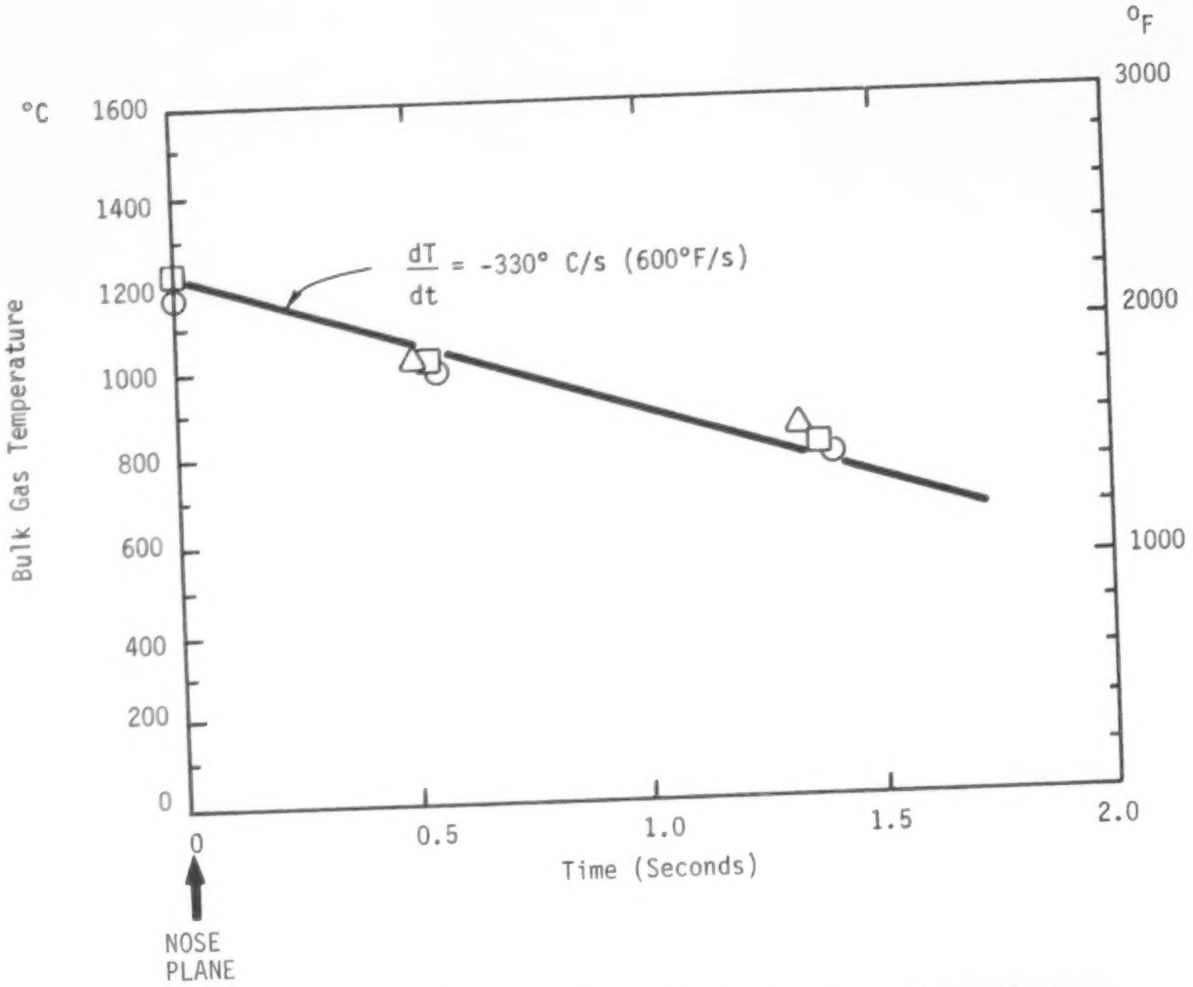


Figure 5-13. Bulk temperature time relationship in the furnace.

5.3 Test Matrix

Two series of tests were conducted to identify the impacts of mixing and dispersion of the sorbent stream with flue gas on the sulfur capture levels. First series of tests involved input-output type measurements to determine the effects of

- jet velocity (jet to cross flow momentum flux)
- number and location of injection jets

on the overall sulfur capture levels. Gas phase sulfur removal efficiencies were determined by making SO_2 measurements before, during and after sorbent injection under the present injection conditions. Tests were conducted at several Ca/S molar ratios between 0.5 and 3.0 to obtain the stoichiometry dependence of SO_2 capture. Table 5-4 summarizes the injection test conditions for the first series of tests. Most of the tests were done with Linwood atmospheric hydrate. Injection locations were at the nose plane and above the nose at the ordinary boiler frame of reference (in the inverted model, below the nose). The alphabetically labeled injection configurations correspond to the configurations sketched in Figure 5-14. The momentum flux ratios were determined based on the flow rate of the carrier air and the sorbent feed rate according to:

$$J = \frac{\rho_{air} V_{carr}^2}{\rho_\infty V_\infty^2} \left(1 + \frac{\dot{M}_{sorb}}{\dot{M}_{air}}\right) \qquad (5\text{-}1)$$

and the carrier air flow rate was adjusted to obtain the desired momentum flux ratios. However, some problems were experienced in the feeding of the sorbents at high Ca/S ratios (especially hydrates) due to the conflicting requirements of minimum carrier flowrates for sorbent transport and the constant momentum flux ratio. Since the sorbent feed rate is a linear function of the Ca/S molar ratio, experiments at high Ca/S ratios needed to be conducted with less air flow in order to keep the momentum flux ratio constant. This caused sorbent transport problems due to plugging of injector

TABLE 5-4. SORBENT INJECTION TEST MATRIX

Sorbent	Injection Location	Injector Configuration	Nozzle Diameter cm.	$J = \frac{\rho_j V_j^2}{\rho_\infty V_\infty^2}$
Linwood	Nose	A	1.59	50
Linwood	Nose	A	1.59	100
Linwood	Nose	A	1.59	150
Linwood	Nose	B	1.59	100
Linwood	+0.5L	A	1.59	50
Linwood	+0.5L	A	1.59	100
Linwood	Nose	C	5.08	30-135
Linwood	Nose	D	2.22	250-1255
Linwood	+3/4L	E	2.22	188
Marblehead	Nose	A	1.59	100
Vicron	Nose	A	1.59	120-150
Vicron	Nose	B	1.59	550-620

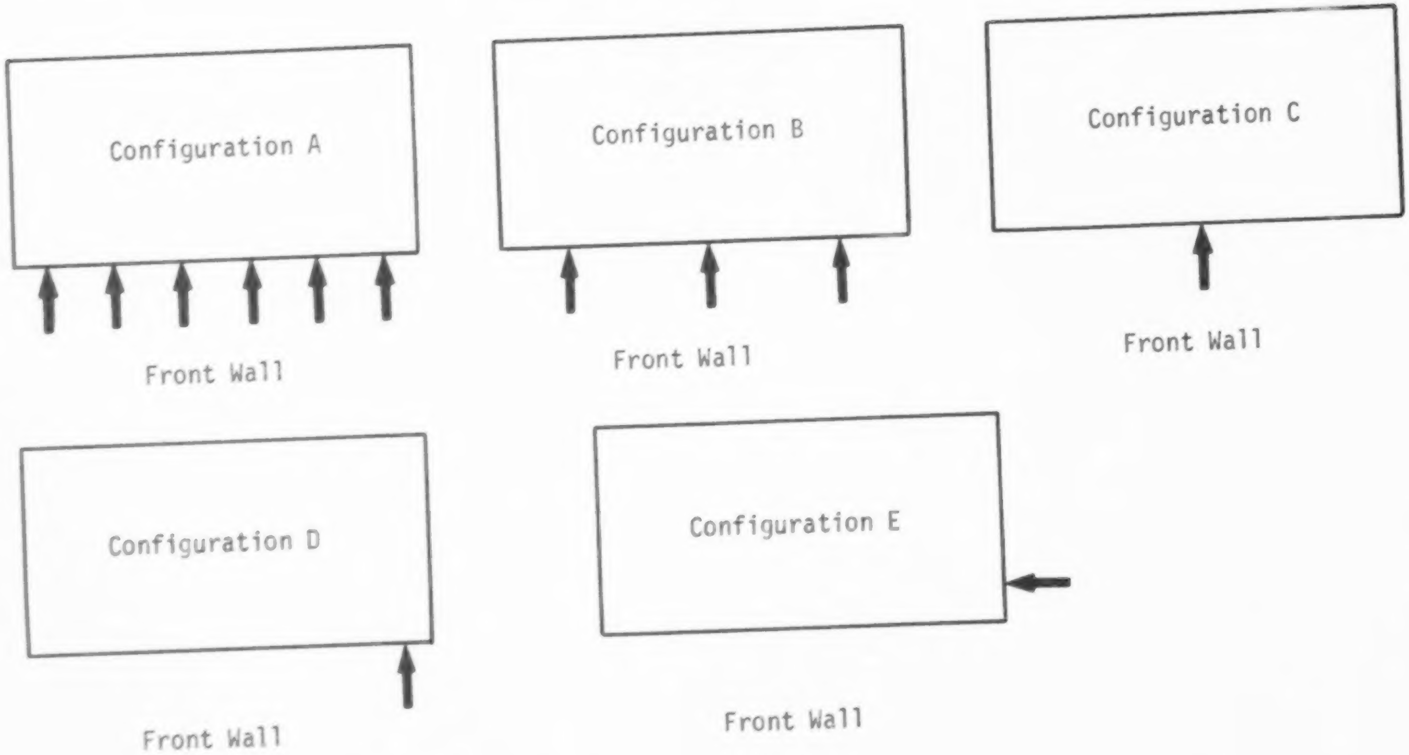

Configuration A
Front Wall
Configuration B
Front Wall
Configuration C
Front Wall
Configuration D
Front Wall
Configuration E
Front Wall

Figure 5-14. Injection configurations.

lines and splitters. Hence, the envelope of the operation for varying the Ca/S ratio at a given momentum flux ratio was limited especially for low momentum flux ratio. In some experiments, the condition of constant momentum flux ratio was relaxed in order to conduct some of the experiments as shown in Table 5-4.

Following these input/output tests, few selected cases were studied in detail. These included gas tracer dispersion measurements for three test configurations. In these tests, a furnace was fired with natural gas and injection jets were seeded with SO_2. Concentration profiles of SO_2 were measured at a downstream plane to determine dispersion.

5.4 Sorbent Injection Test Results

In this section, the test results are presented for the test conditions described in Subsection 5.3. Interpretation of these results based on empirical and computational models are given in Section 5.6. In the following, the effects of injection parameters are discussed separately.

5.4.1. Effect of Momentum Flux Ratio

A series of tests were conducted with Linwood atmospheric hydrate to determine the effect of jet velocity (or momentum) on the overall sulfur capture levels. Jet to cross flow momentum ratio was varied from 50 to 180. Sulfur capture was measured in a range of Ca/S molar ratios between 0.5 and 3.0. Figure 5-15 shows the sulfur capture at the low momentum flux ratio between 51 and 66. As mentioned before, due to the feeding difficulties at low velocities, only a few data were successfully obtained. Results showed relatively good capture (approximately 49 percent at Ca/S = 2) with injection at the nose plane at a temperature of about 1290°C. It should be kept in mind that this temperature was not necessarily the bulk peak temperature achieved in the sorbent jet. Although parts of the jet may have experienced temperatures as high as 1290°C, the bulk of the jet reached a maximum temperature lower than this value.

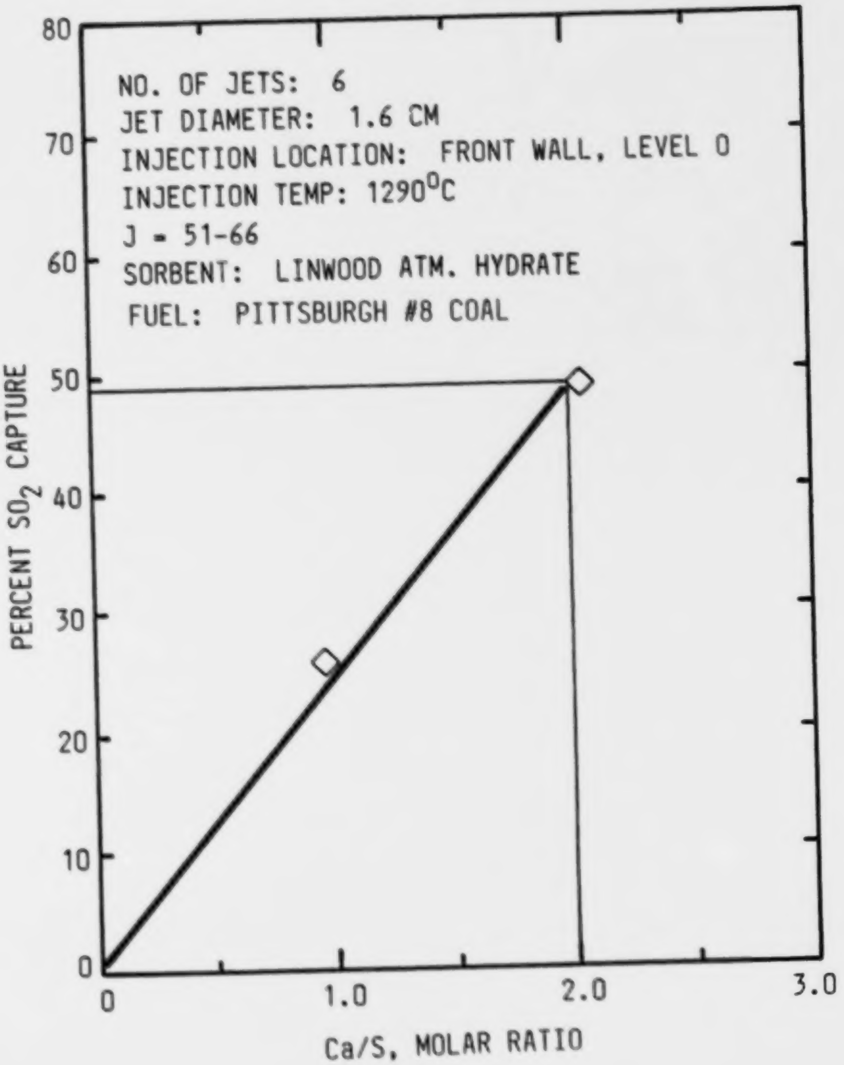


Figure 5-15. Sulfur capture with six jets on the front wall at the nose plane at low jet momentum with Linwood atmospheric hydrate.

Figure 5-16 shows sulfur capture at the medium jet momentum flux ratio between 97 and 123. The results indicate that the sulfur capture levels were similar to those at the low momentum flux ratio. The sulfur capture was approximately 50 percent at Ca/S = 2.0. This was surprising because the momentum flux ratio was one of the important factors in determining the trajectory of the jets in cross flow. However, a detailed analysis based on computational models of jet mixing and calcination/sulfation discussed in Section 5.6, indicated that the sulfur capture was not sensitive to the jet to cross flow momentum flux ratio. Similar results were obtained at the high momentum flux ratio shown in Figure 5-17. The sulfur capture was about 51 percent at Ca/S molar ratio of 2.0. Figure 5-18 summarizes the results shown earlier and indicates that there was virtually no effect of jet momentum on the sulfur capture levels within the range the jet velocities varied during these experiments. A change of a factor of three in the momentum flux ratio corresponded approximately (*) to a factor of 1.7 in the jet velocity. This level of change in velocity did not cause any significant change in the sulfur capture levels.

5.4.2 Effect of Number of Jets

Because of the observed insensitivity of sulfur capture to the momentum flux ratio, the impact of the number of injection jets, on sulfur capture was tested. Sorbent was injected through 3 injectors of the same size at a momentum flux ratio between 81 and 114. Surprisingly, the effect of decreasing the number of injectors from six to three was negligible as shown in Figure 5-19. However, the same injection temperature (1300°C for six jets) could not be achieved for the three jet experiment. It may have been that injection temperature effect masked the dispersion effect exhibited by the number of injection jets. Following this observation, tests were conducted with one jet on the front wall near one corner (see Figure 5-14, Configuration D) Results showed a significant degradation of sulfur capture

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(*) Approximation comes from the additional change in the solid loading of one jet, see equation (5-1).

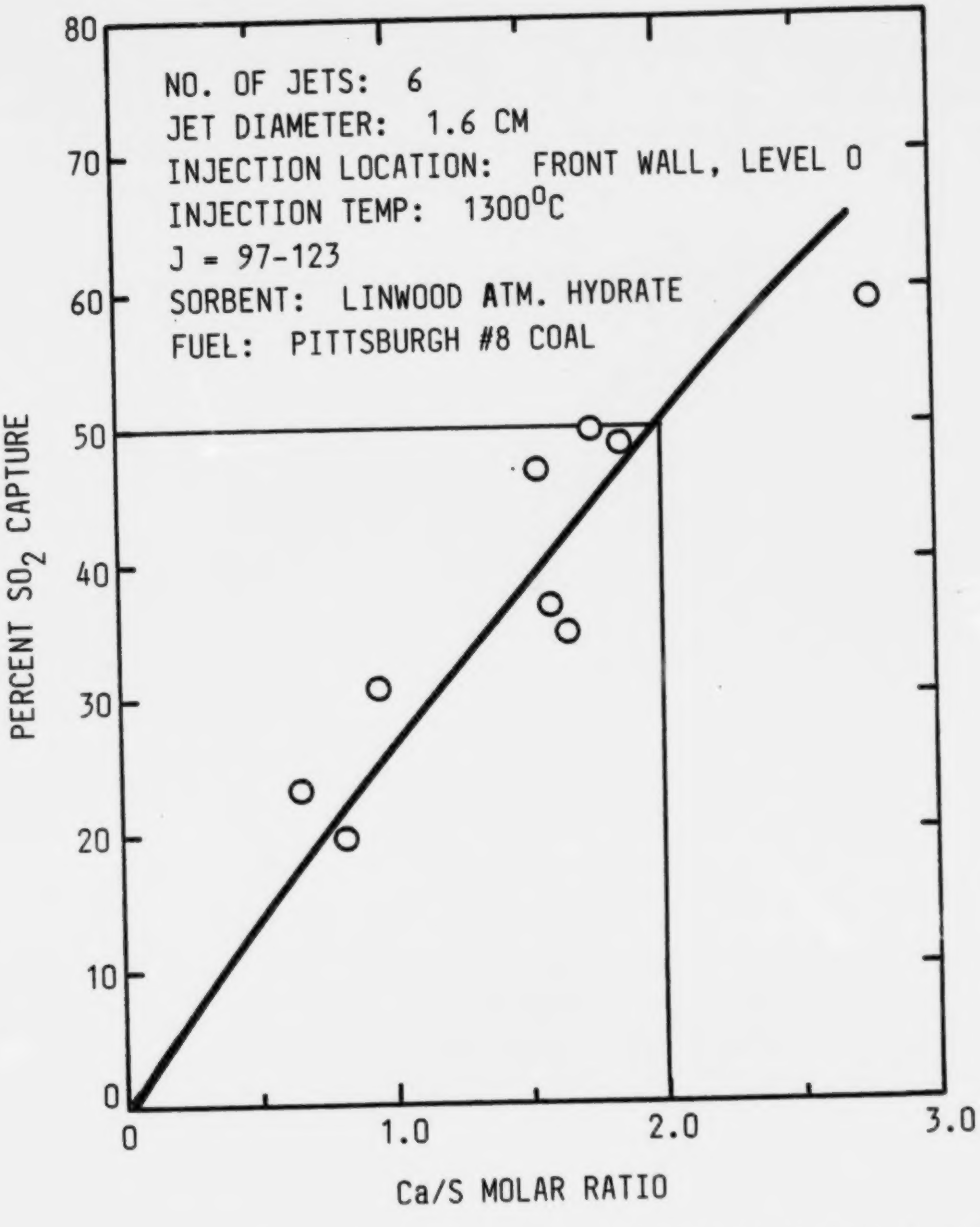


Figure 5-16. Sulfur capture with six jets on the front wall at the nose plane at medium jet momentum with Linwood atmospheric hydrate.

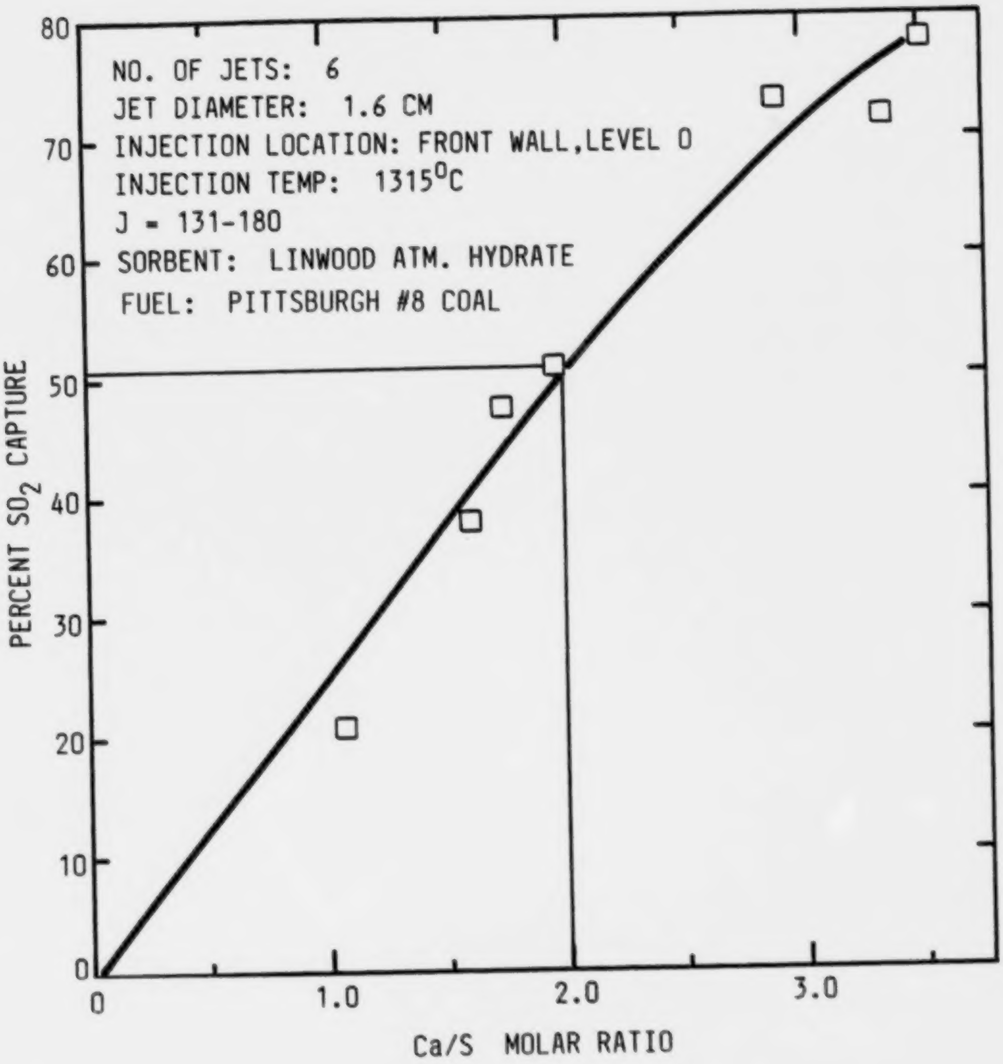


Figure 5-17. Sulfur capture with six jets on the front wall at the nose plane at high jet momentum with Linwood atmospheric hydrate.

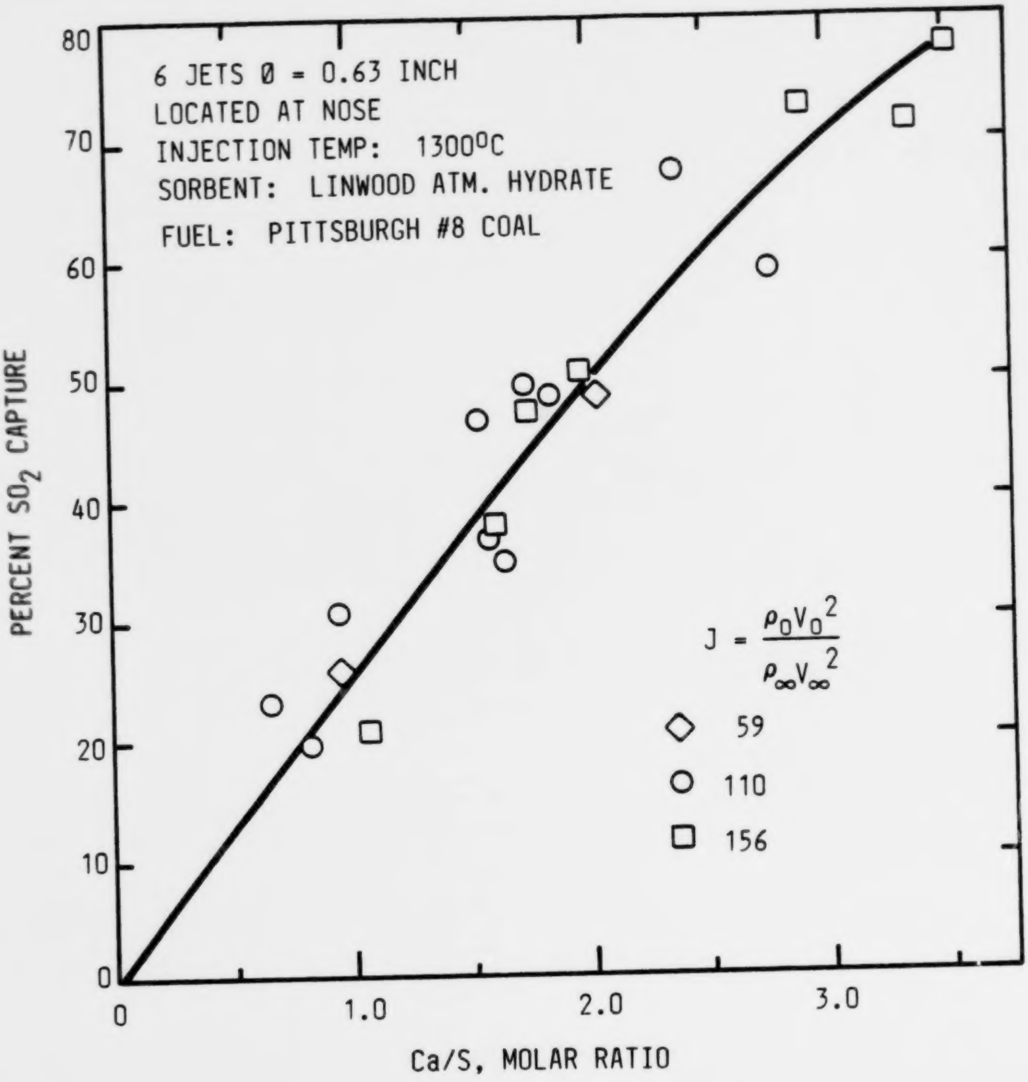


Figure 5-18. Summary of sulfur capture results of three jets to cross flow momentum flux ratios.

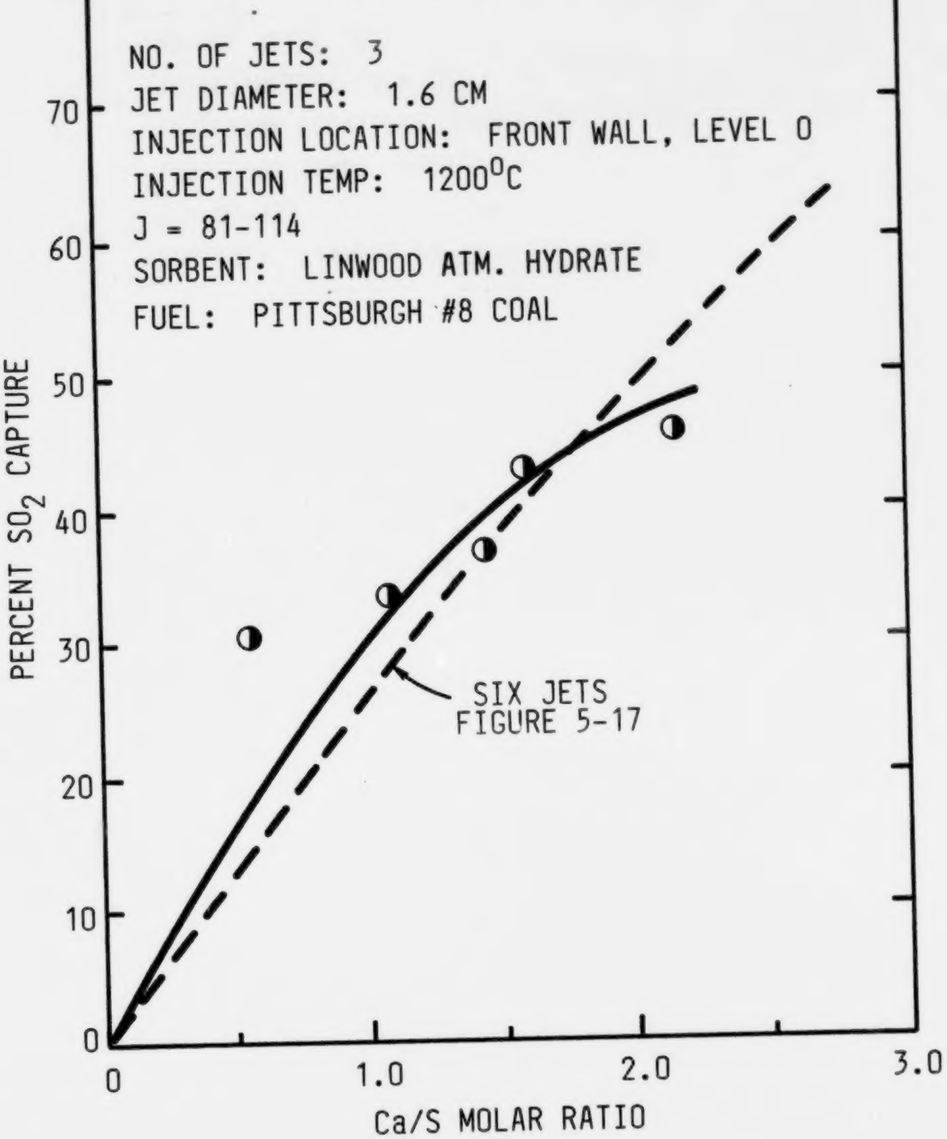


Figure 5-19. Effect of dispersion on sulfur capture as exhibited by reduced number of jets.

when sorbent was injected through a single jet as shown in Figure 5-20. For this case and the three jet case, the injection temperatures were similar. Hence, degradation of sulfur capture was mainly due to dispersion. This was expected since the sulfur capture would be ultimately be affected by the maldistribution of the sorbent. A similar result was obtained for a single 5.0 cm jet located at the center of the nose plane at the front wall as shown in Figure 5-21. The sulfur capture levels were lower than the corresponding six and three jet injection configurations. These results could be explained based on the dispersion patterns obtained in the isothermal test model and the combustor as it is discussed in Section 5.6.

5.4.3 Effect of Injection Location (Temperature)

A few tests were conducted to study the impact of injection location on the sulfur capture with Linwood atmospheric hydrate. Sorbent was injected through six injectors half duct depth above the nose plane (see Figure 5-4, location + 0.5L). The temperature at the injection location was approximately 1200°C compared to 1300°C at the nose plane. The measurements indicated that there was no significant effect on the sulfur capture levels as shown in Figure 5-22.

5.4.4 Effect of Sorbent Type

A limited number of tests were conducted to compare the effect of sorbent type on sulfur capture under similar mixing conditions. Figure 5-23 shows the sulfur capture with Vicron 45-3 and comparison with Linwood atmospheric hydrate under similar mixing conditions. The sulfur capture level was about 30 to 35 percent at Ca/S ratio of 2.0 with Vicron 45-3 compared to 45 to 55 percent with Linwood atmospheric hydrate.

The capture levels with limestone were in agreement with other bench scale data obtained under similar injection conditions. For example, the capture level is approximately 30 percent at Ca/S ratio of 2.0 in the Controlled Temperature Tower (CTT) furnace. The sulfur capture was slightly degraded when Vicron was injected through three injection ports. This effect

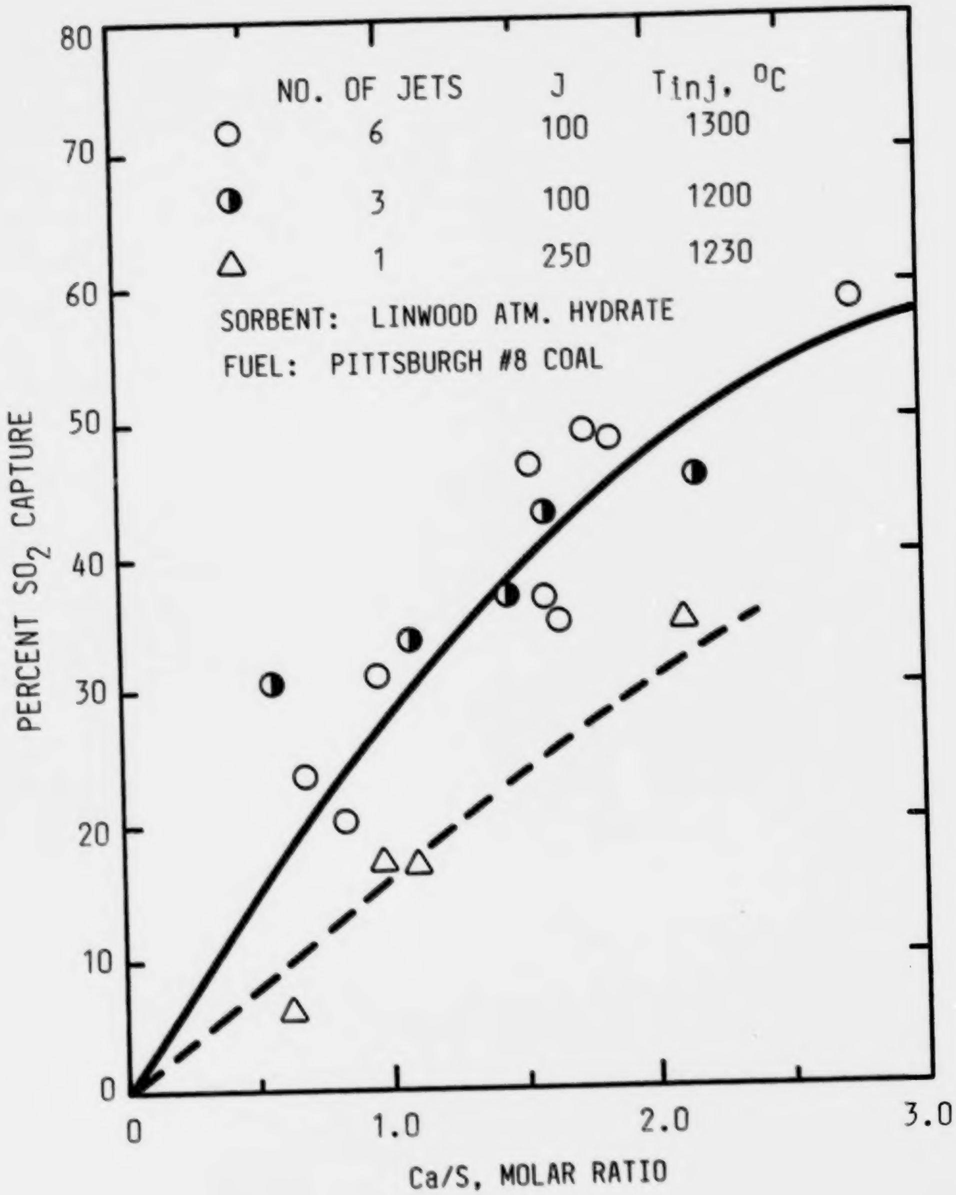


Figure 5-20. Effect of dispersion on sulfur capture as exhibited by the reduced number of jets: one jet near the corner.

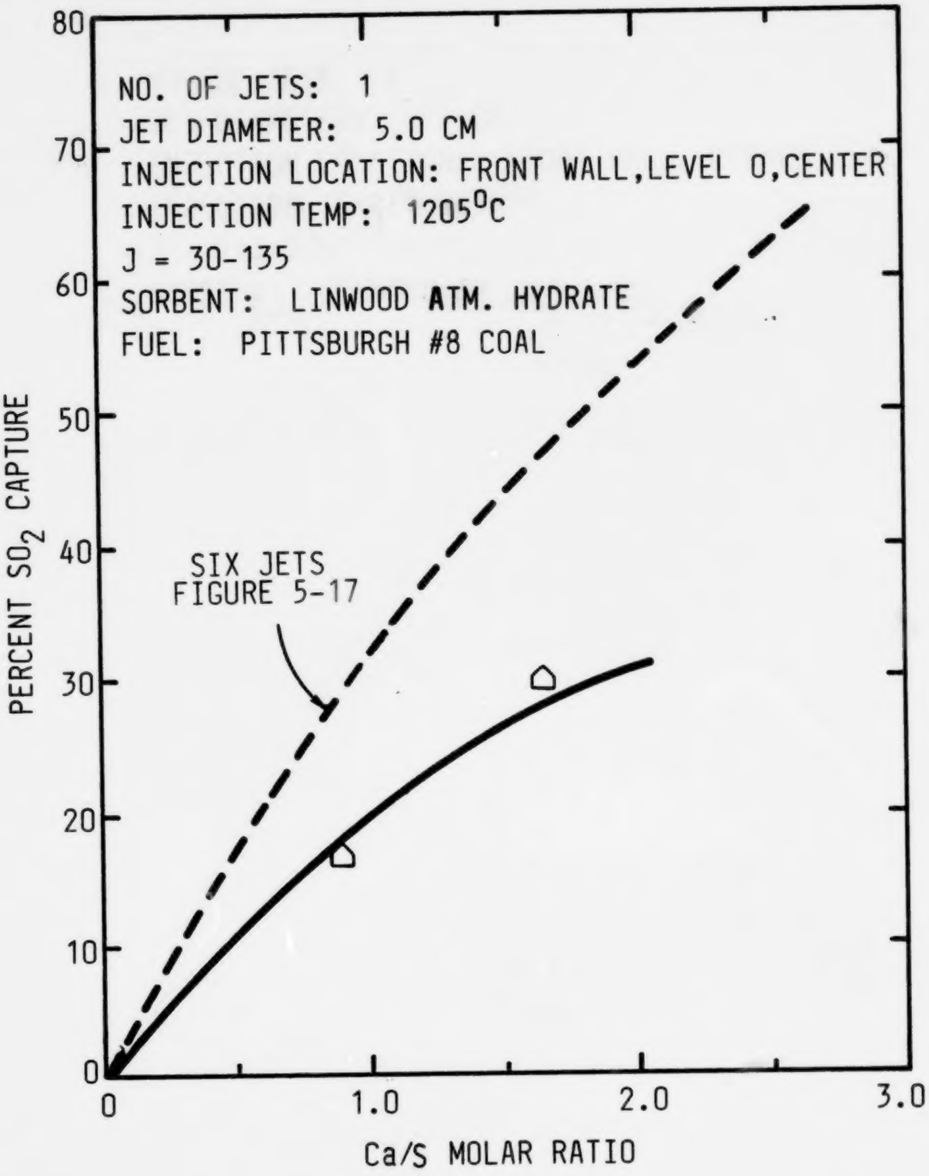


Figure 5-21. Effect of dispersion on sulfur capture as exhibited by the reduced number of jets: one jet at the center.

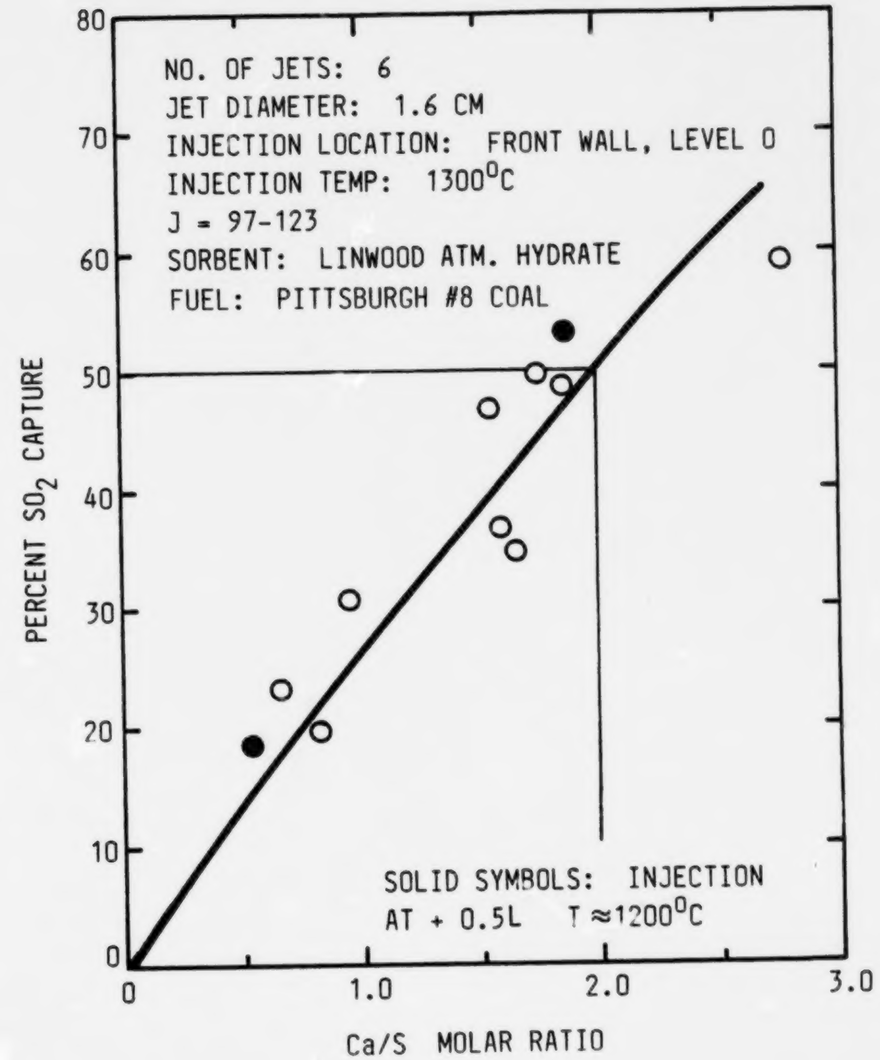


Figure 5-22. Impact of injection location (temperature) on sulfur capture with six jets and Linwood atmospheric hydrate.

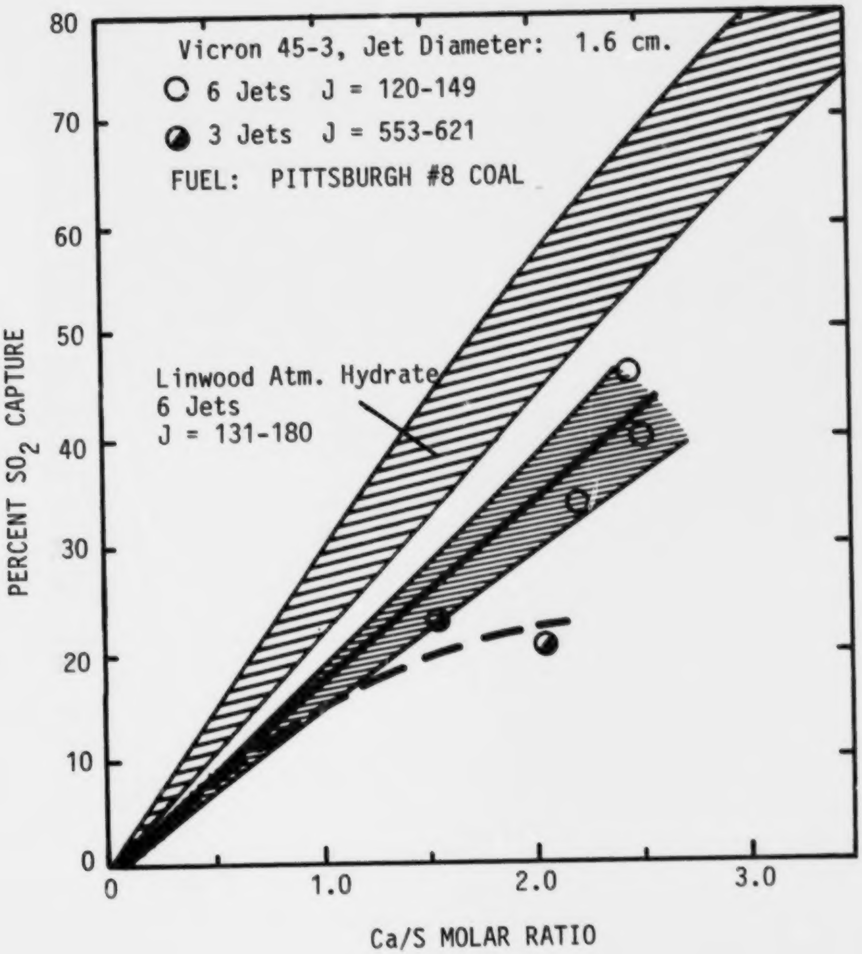


Figure 5-23. Comparison of performance for Linwood atmospheric hydrate and Vicron 45-3 limestone.

was more pronounced at higher Ca/S ratios. This is probably due to the amplified effect of sorbent maldistribution at higher Ca/S ratios.

The performance of Marblehead atmospheric hydrate was also compared with that of Linwood atmospheric hydrate in a short preliminary trial. Figure 5-24 shows the results from two injection tests and compares them with Linwood atmospheric hydrate performance. Although the sulfur capture at high Ca/S ratio appeared to be higher than that with Linwood, confidence should not be placed on this single data point taken in a short time period during which the sorbent feed rate may have experienced fluctuations. All earlier bench scale studies indicated that the performance of Marblehead was similar to Linwood and in some cases the performance was inferior to Linwood. Hence, it was difficult to infer the differences in sulfur capture performance based on these two data points.

Detailed gas tracer concentration measurements were made to aid in understanding of the mixing/dispersion effects on sulfur capture. The next subsection describes these measurements followed by the interpretation of the overall sulfur capture data.

5.5 Detailed Concentration Measurements

Steady-state SO_2 tracer concentration measurements were made in the combustion facility to determine the dispersion of the injection fluid into the hot furnace gas stream. Three cases selected for these measurements were those which showed differences in sulfur capture levels attributable to the degree of dispersion or mixedness. Specifically, tests were conducted for

- six, 1.58 cm. diameter jets injected at the nose level at a momentum flux ratio of 96.
- a single, 5.08 cm. diameter jet injected at the nose level at a momentum flux ratio of 15.

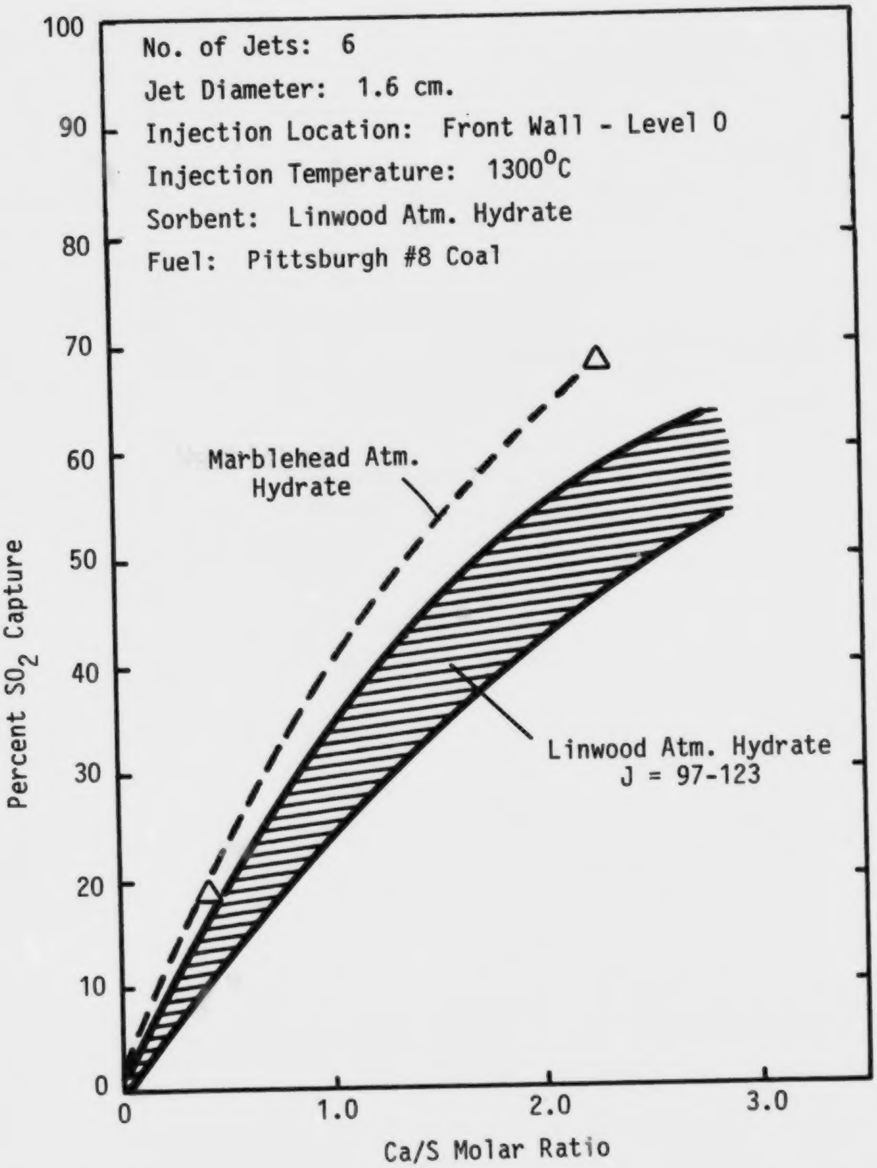


Figure 5-24. Comparison of performance for Linwood and Marblehead atmospheric hydrates.

- a single, 2.22 cm. diameter jet injected near the side wall at the nose level at a momentum flux ratio of 170.

A small amount of SO_2 gas was introduced into the injection air at ambient temperature. Gas tracer concentrations were measured at two downstream planes over a grid of measuring points. The local measured SO_2 concentrations were normalized with the measured exhaust SO_2 concentration which represented the well-mixed concentration level. Measured well-mixed concentration was checked against the calculated well-mixed concentrations based on the flowrates. The agreement between the two values was good. Figures 5-25, 5-26 and 5-27 show the normalized, steady-state concentration profiles for the three cases mentioned above. Measurements suggest that the tracer distribution for the six jets was much more uniform than the other two cases. The single 5.08 cm. jet spread out to cover a large portion of the superheater entrance plane, but high tracer concentrations still indicated that the jet stream was not thoroughly mixed. The single-corner jet represented the worst case in terms of its spread and the high concentration levels at the superheater entrance plane.

5.6 Interpretation of Test Results

The two key results from the pilot scale tests were

- sulfur capture was insensitive to the velocity (or momentum) of injection jets within the range this parameter was varied.
- dispersion of sorbent across the furnace flow became important when the sorbent was highly maldistributed in the furnace flow.

The first of these findings was surprising since the dispersion profiles were expected to be affected by the changes in momentum flux ratio. However, the sulfur capture process taking place in a sorbent jet is complex, and dependent on the residence times in the injection jet, the temperatures the sorbent particles experience as they travel in the jet and the concentration of SO_2 around the particles. Jet momentum has an impact on trajectory and

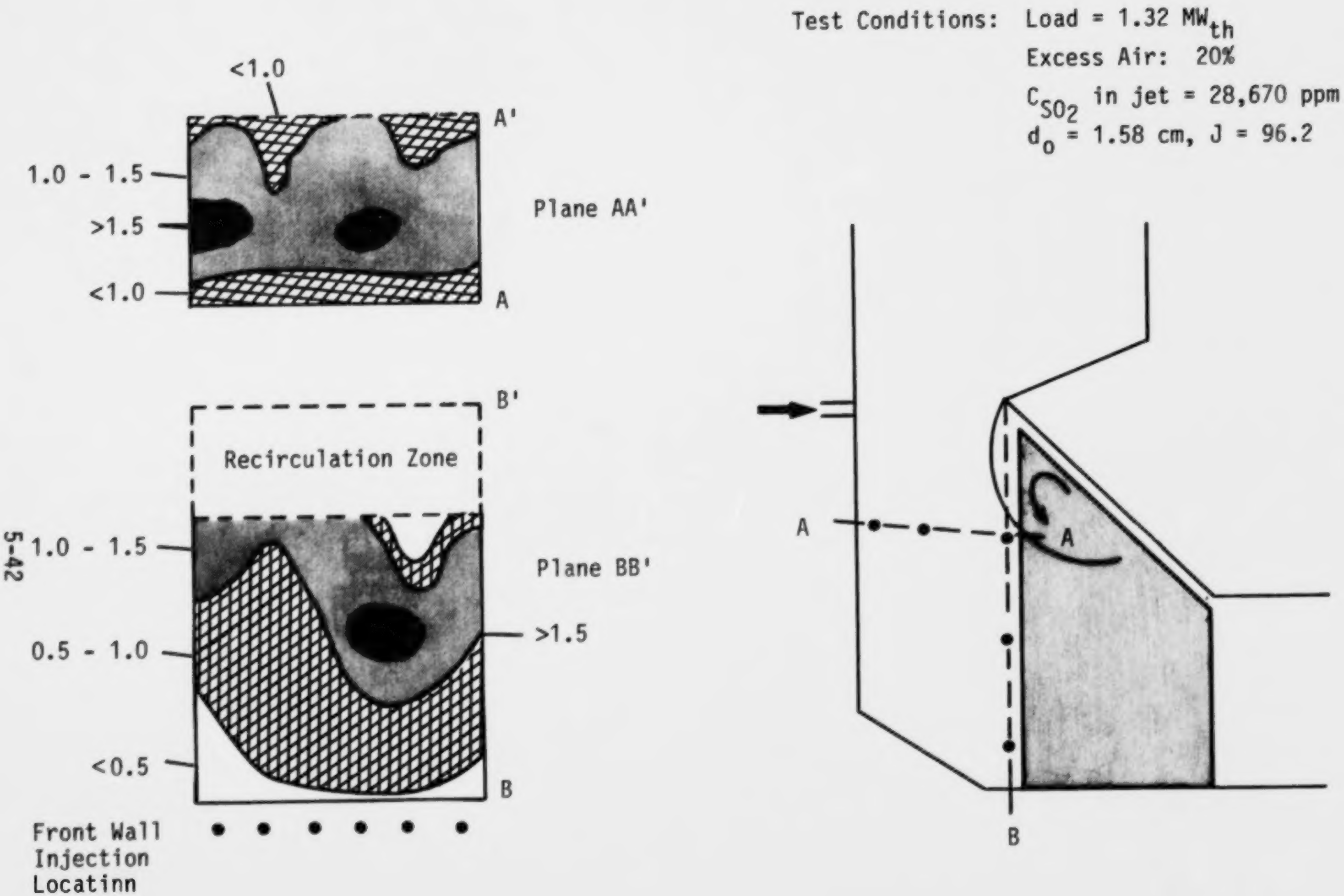
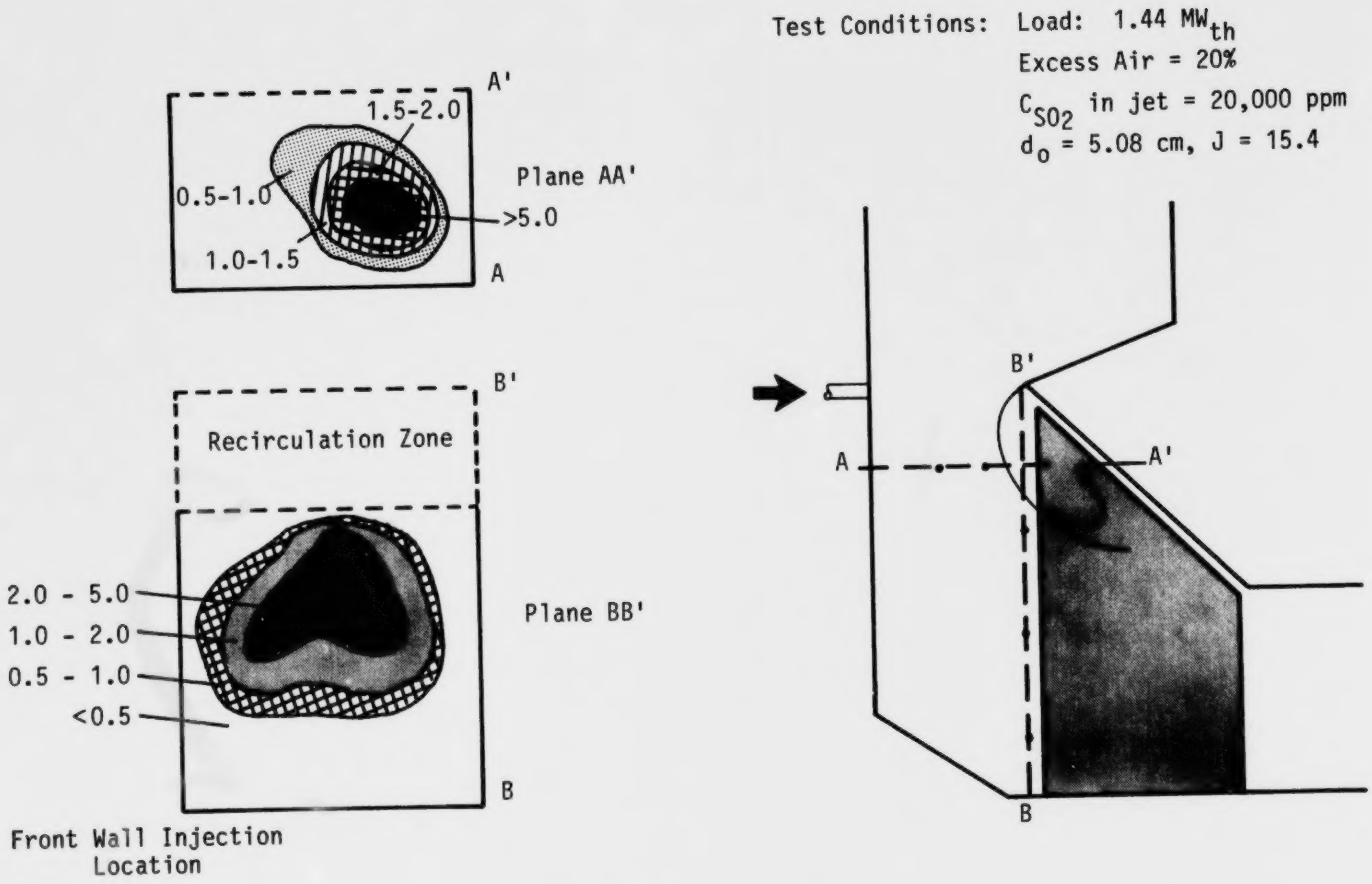

Test Conditions: Load = 1.32 MW_{th}
Excess Air: 20%
C_{SO_2} in jet = 28,670 ppm
d_o = 1.58 cm, J = 96.2
<1.0
1.0 - 1.5
>1.5
<1.0
A'
A
Plane AA'
B'
Recirculation Zone
1.0 - 1.5
0.5 - 1.0
<0.5
>1.5
B
Plane BB'
Front Wall
Injection
Locatinn
A
A
B

Figure 5-25. SO_2 tracer concentration profiles measured for six jets injected at the nose plane.



A'
1.5-2.0
0.5-1.0
1.0-1.5
>5.0
A
Plane AA'
B'
Recirculation Zone
2.0 - 5.0
1.0 - 2.0
0.5 - 1.0
<0.5
Plane BB'
B
Front Wall Injection Location
B'
A
A'
B

Test Conditions: Load: 1.44 MW_{th}
Excess Air = 20%
C_{SO_2} in jet = 20,000 ppm
d_o = 5.08 cm, J = 15.4

Figure 5-26. SO_2 tracer concentration profiles measured for one jet injected at the nose plane center.

Test Conditions: Load = 1.49 MW_{th}
Excess Air = 30%
C_{SO_2} in jet = 74,670 ppm
d_o = 2.22 cm, J = 170

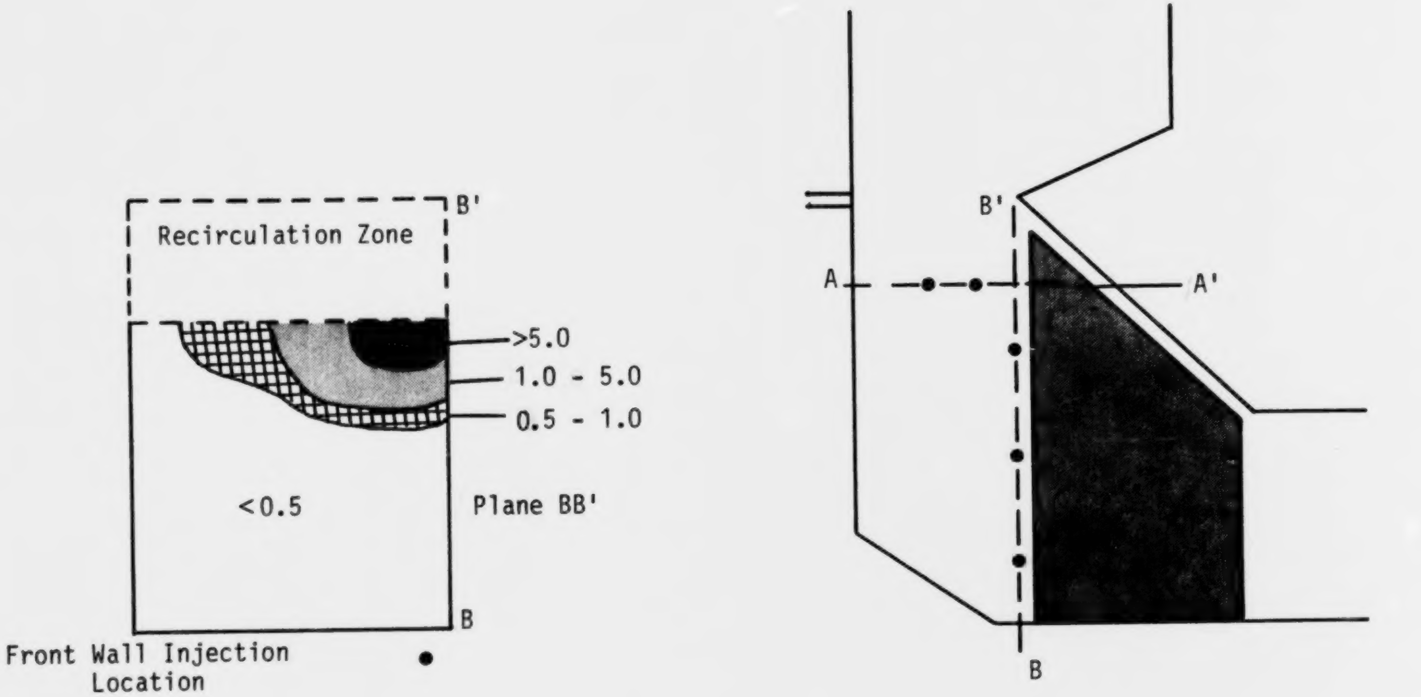

B'
Recirculation Zone
>5.0
1.0 - 5.0
0.5 - 1.0
<0.5
Plane BB'
B
Front Wall Injection Location
B'
A
A'
B

Figure 5-27. SO_2 tracer concentration profiles measured for one jet injected at the nose plane corner.

entrainment of the injection jets. Thus, it could have an impact on the velocity, temperature, concentration variations along the jet.

In order to simultaneously account for all these effects, the computational jet model, described in Section 4.0, was used in conjunction with a developmental calcination/sulfation model to estimate the progress of sulfur capture in the injection jets. The calcination/sulfation model was calibrated against experimental data to predict the sulfur capture with Linwood atmospheric hydrate in the Controlled Temperature Tower (CTT) furnace. Figure 5-28 shows the prediction of CTT data with the calibrated calcination/sulfation model for Linwood atmospheric hydrate. Figure 5-29 summarizes the methodology used to estimate the sulfur capture from the jet and the calcination/sulfation models. First, the furnace gas temperature profiles and the injection parameters (jet diameter, velocity, temperature, sorbent mass loading) and cross flow conditions (velocity, density) were input into the jet model to predict the bulk temperature-time and Ca/S-time relationships in the jet until the jet entered the superheater plane. At this location, it was assumed that no additional mixing takes place after this point. The predicted profiles of temperature-time and Ca/S-time were input into the calcination/sulfation model to predict the sulfation of the sorbent as it travelled in the jets. Figures 5-30, 5-31 and 5-32 show the computed temperature-time, Ca/S-time, and sulfur capture-time profiles for the conditions of the experiments carried out at J = 59, 100 and 150. The sulfur capture values based on the measured SO_2 concentrations at the furnace exit were also shown on these figures for comparison. In all cases, the predictions were in fair agreement with the range of measured values. Figure 5-33 summarizes the measured and predicted dependence of sulfur capture on the momentum flux ratio. Although predictions exhibited a weak dependence on momentum flux ratio, this was within the accuracy level of the experimental results. Hence, the experimental findings were confirmed to a certain extent with the predictions. The pilot scale test data therefore provides a means of validating the modeling and injection system design approach, and it is not expected that such data can be translated directly into full scale furnace performance. Due to the complexity and the coupling of the mixing, calcination and sulfation processes, a modeling approach, such as that

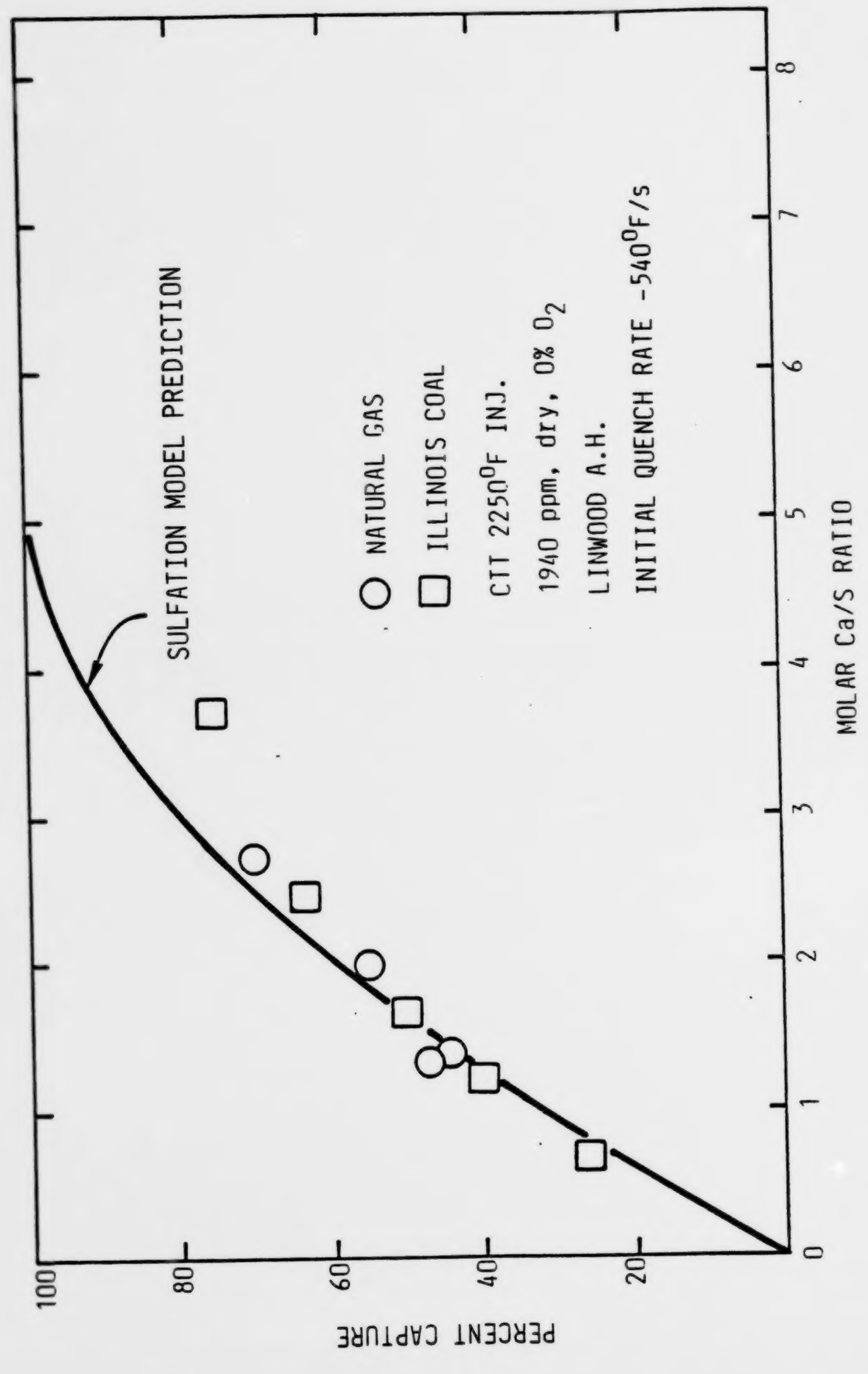


Figure 5-28. Predictions of CTT data with calibrated calcination/sulfation model.

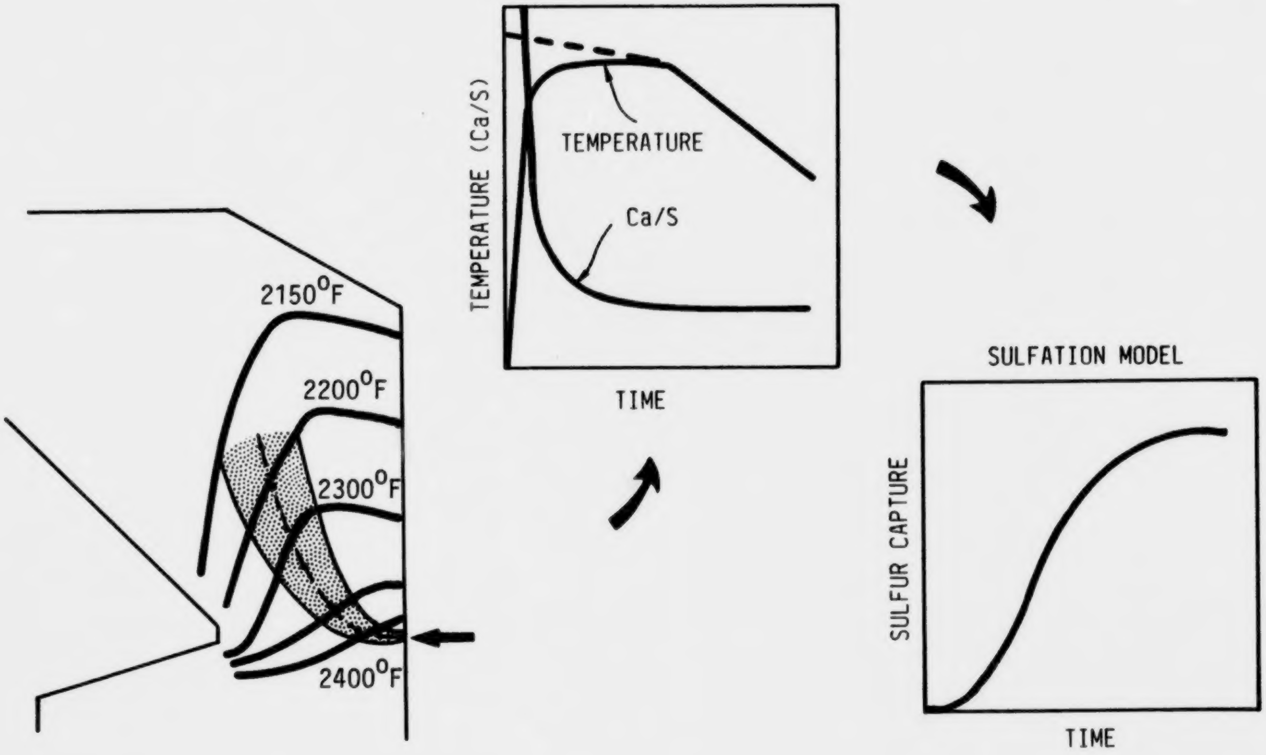

2150°F
2200°F
2300°F
2400°F
TEMPERATURE (Ca/S)
TEMPERATURE
Ca/S
TIME
SULFATION MODEL
SULFUR CAPTURE
TIME

Figure 5-29. Schematic of the computational prediction scheme.

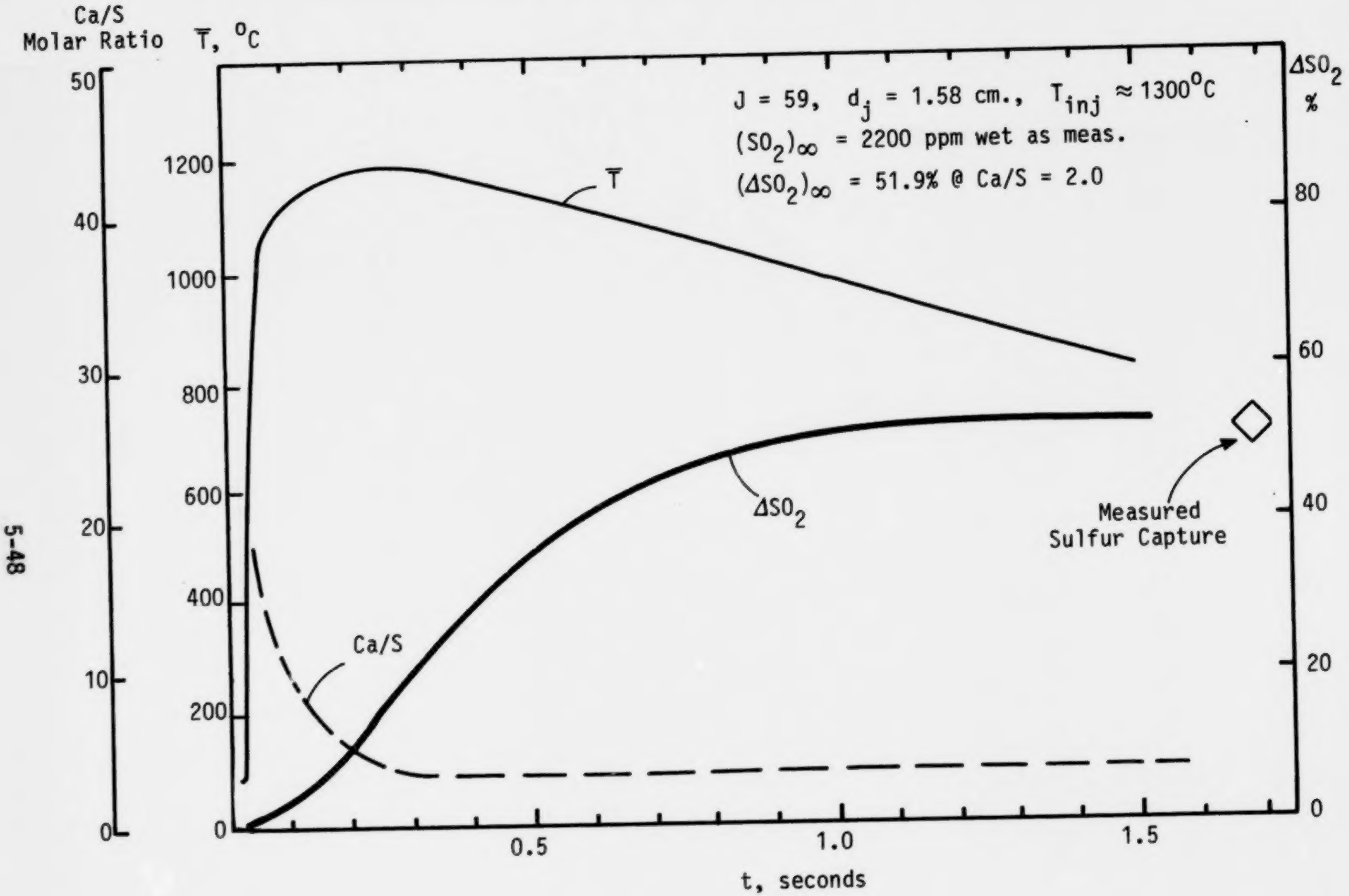


Figure 5-30. Computed profiles of temperature-time, Ca/S-time and ΔSO_2-time profiles for the simulation of experiments conducted at J = 59.

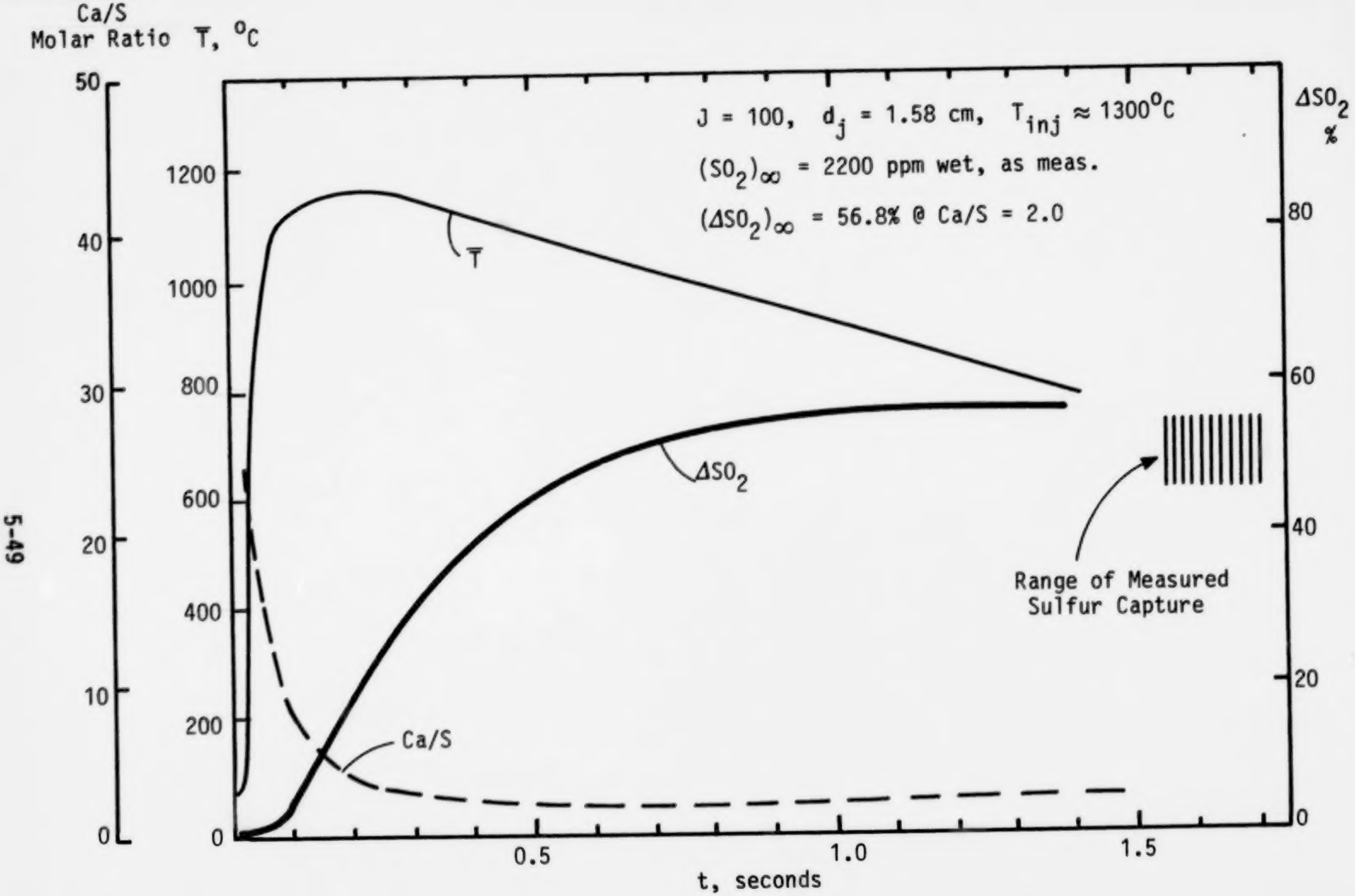


Figure 5-31. Computed profiles of temperature-time, Ca/S -time and ΔSO_2-time profiles for the simulation of experiments at J = 100.

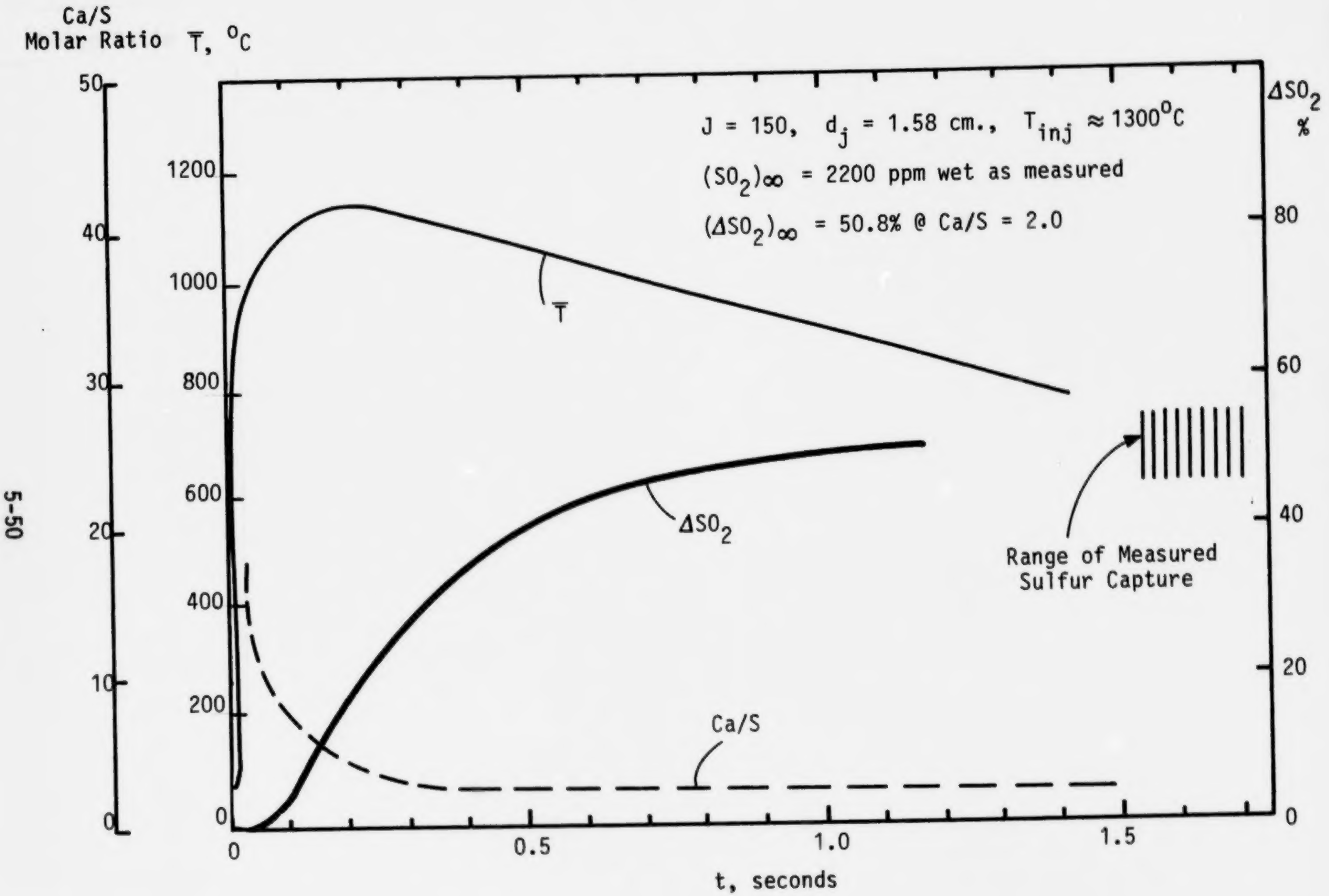


Figure 5-32. Computed profiles of temperature-time, Ca/S-time and ΔSO_2-time profiles for the simulation of experiments at $J = 150$.

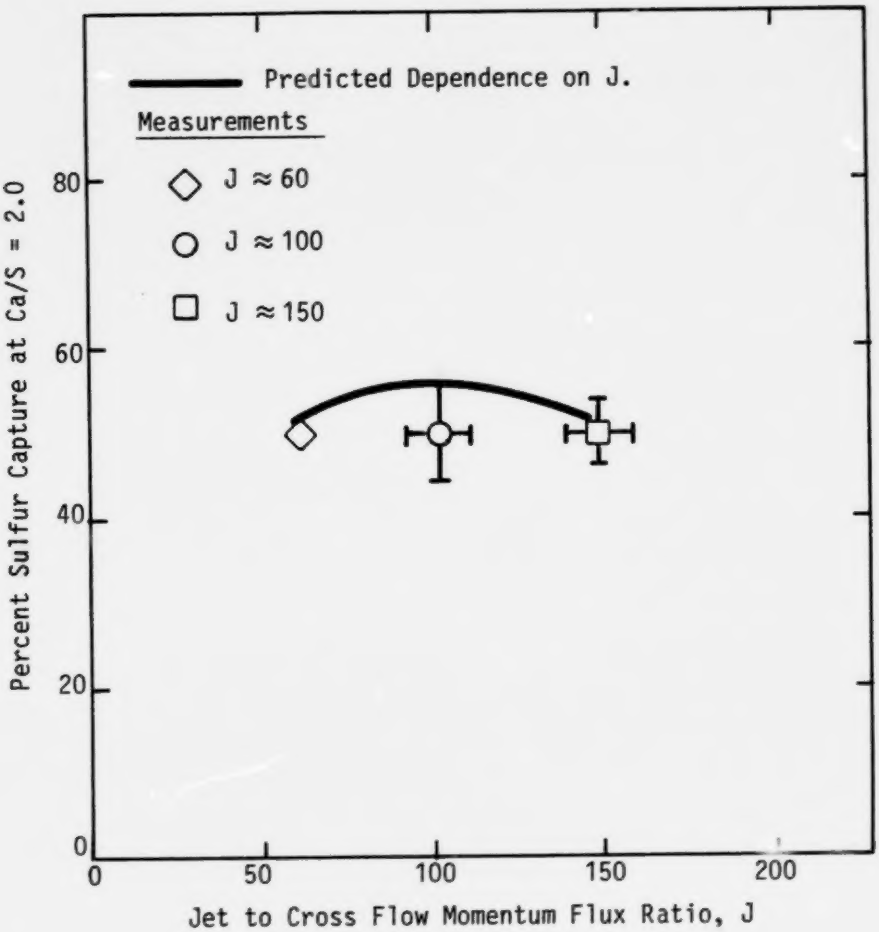


Figure 5-33. Comparison of trends of predicted and measured sulfur capture as a function of jet to cross flow momentum ratio.

described here, provides the only means of interpreting the overall sulfur capture data, and full scale performance which bear the combined effects of these parameters.

The second finding from the pilot scale experiments was the effect of dispersion on sulfur capture. This was observed when dispersion was inhibited by reducing the number of jets, thereby degrading the dispersion of the sorbent in the furnace flue gas stream. This was shown to be true by the dispersion measurements carried out in the combustion facility as described in the previous subsection. In order to predict the effect of dispersion on sulfur capture, an empirical scheme based on measured dispersion profiles was used to interpret the experimental results. Figure 5-34 shows the methodology of the empirical prediction scheme. In this approach, the measured steady-state tracer concentration profiles are utilized to determine the local Ca/S molar ratio distribution across a plane downstream of sorbent injection plane. This is done simply by multiplying the overall well-mixed Ca/S molar ratio with the normalized tracer concentration (local concentration divided by the well-mixed exhaust value) values. The local Ca/S molar ratios can then be used in conjunction with a sulfur capture versus Ca/S molar ratio curve obtained under similar experimental conditions in a combustor where effect of mixing is small. These data allow determination of the individual sulfur capture contributions of the various furnace streams based on the local Ca/S stoichiometries. The final step in the procedure is to superimpose the effect of the flow field, i.e. distribution of the furnace gas flow, on the overall sulfur capture. This is achieved by integrating across the plane, or in this case by carrying out the sum,

$$\Delta SO_{2,\mathrm{overall}} = \sum_i \frac{M_i}{M_T} (\Delta SO_2)_i \qquad (5\text{-}2)$$

where M_i/M_T represent the flow distribution and summation is carried out across the cross section.

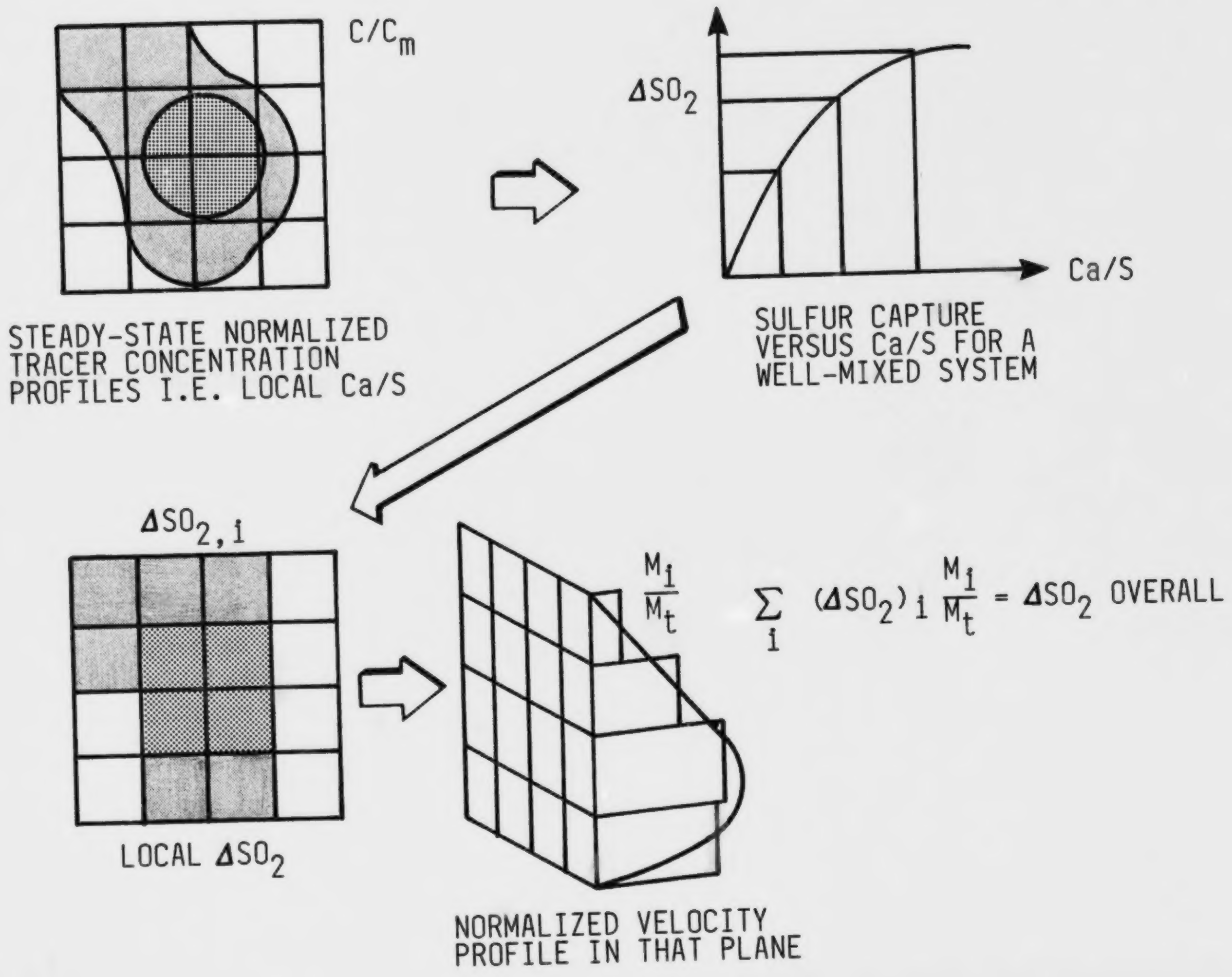

C/C_m
STEADY-STATE NORMALIZED TRACER CONCENTRATION PROFILES I.E. LOCAL Ca/S
ΔSO_2
Ca/S
SULFUR CAPTURE VERSUS Ca/S FOR A WELL-MIXED SYSTEM
$\Delta SO_{2,i}$
LOCAL ΔSO_2
$\frac{M_i}{M_t}$
NORMALIZED VELOCITY PROFILE IN THAT PLANE
$\sum_i (\Delta SO_2)_i \frac{M_i}{M_t} = \Delta SO_2$ OVERALL

Figure 5-34. Empirical methodology to predict effect of dispersion on sulfur capture.

This exercise was performed for the experiments described before by utilizing the sulfur capture data obtained in the Controlled Temperature Tower furnace which is a cylindrical furnace with an inner diameter of 20 cm operating at 17.6 kW. In this furnace, sorbent is injected into the axial flow of furnace gases at right angles which provides a very rapid dispersion of the sorbent at this small scale. Predictions were based on Linwood atmospheric hydrate injection at about 1250°C. Dispersion profiles measured in the modified section of a tower furnace were used in superimposing the effect of dispersion. In this analysis, a selection had to be be made on the location of the plane where dispersion profiles should be evaluated. Calculations were performed to determine the impact of this on the predictions. Figure 5-35 and 5-36 show the experimental data and two prediction lines for dispersion profiles at approximately 1050°C and 1150°C temperature isoplanes. It is apparent that the dispersion profile measured upstream near 1150°C gave a much better agreement for both cases with the experimental data than the 1050°C plane (superheater entrance). It can be conjectured that the representative dispersion plane, if it exists, should be at a temperature where sulfation reactions are fastest. Based on the calcination-sulfation studies, this temperature lies between 1100 and 1200°C. Hence, the use of this dispersion plane was qualitatively justified. Figure 5-37 shows the corresponding comparison of measured sulfur capture with the predictions for a single corner jet. The further agreement of the experiments with predictions is believed to be an indication of the validity of this approach. This approach, however, does not consider the evolution of mixing between the point jet is injected into the furnace flow stream and the location where mixing is complete. In order to reveal these effects, the jet model was used in conjunction with the sulfation model to determine the effects of evolving jet dispersion along the jet before the jets enter the superheater. The computational procedure, described before, was applied to the single jet cases. The results are shown in Figures 5-38 and 5-39. The measured sulfur capture values were shown on the right side of the figures for comparison. It can be seen that this approach also could predict the degradation of sulfur capture with poor dispersion reasonably well.

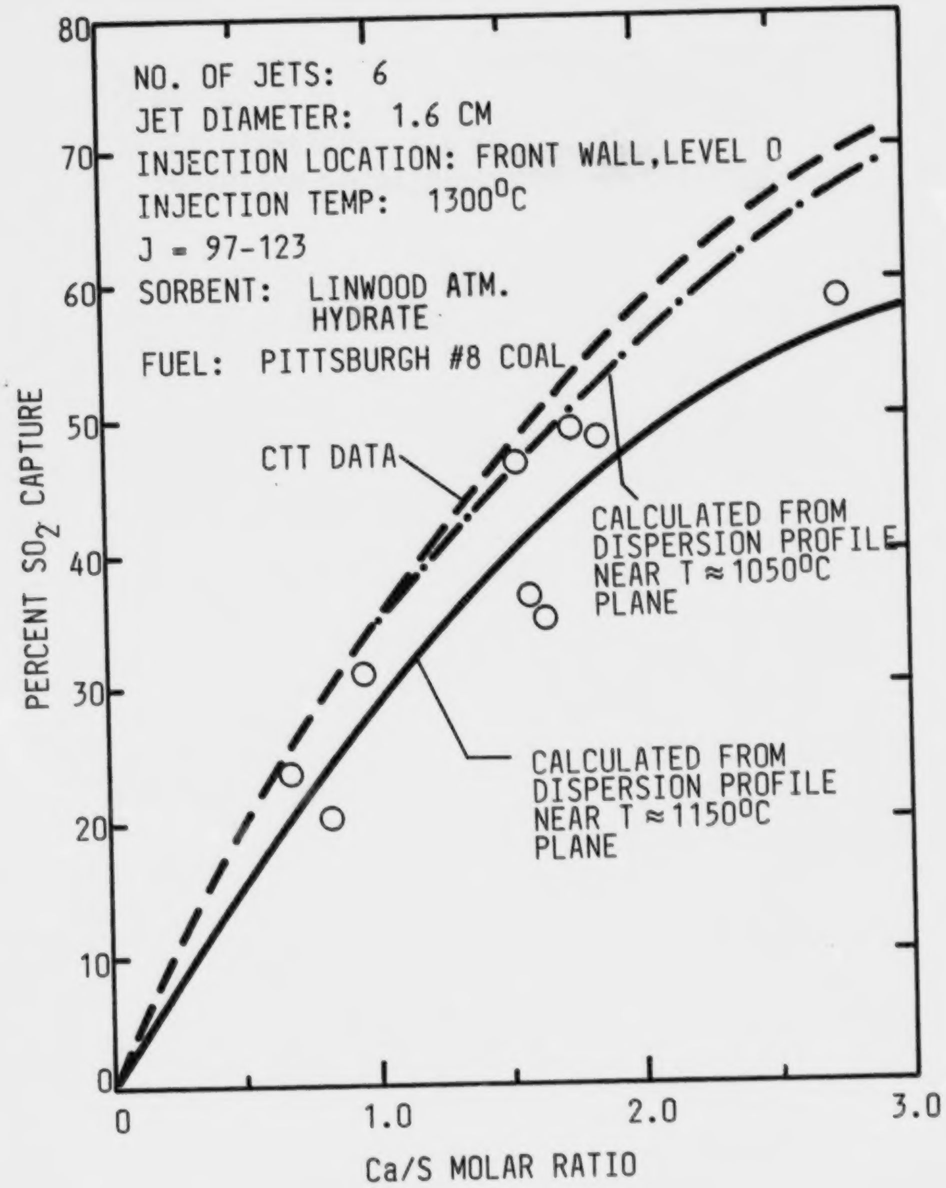


Figure 5-35. Predicted effect of dispersion on sulfur capture for six jets at the nose plane.

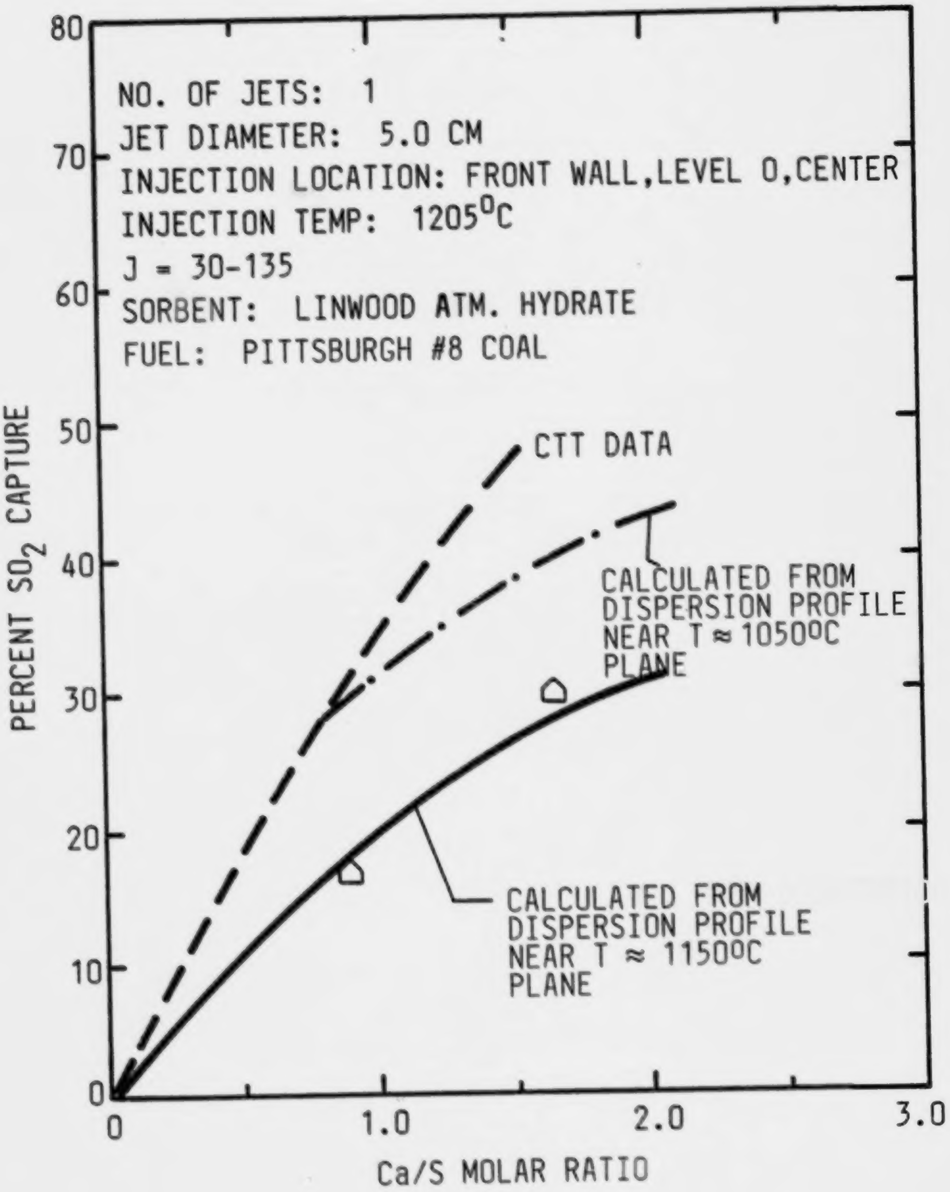


Figure 5-36. Predicted effect of dispersion on sulfur capture for one jet at the center of nose plane.

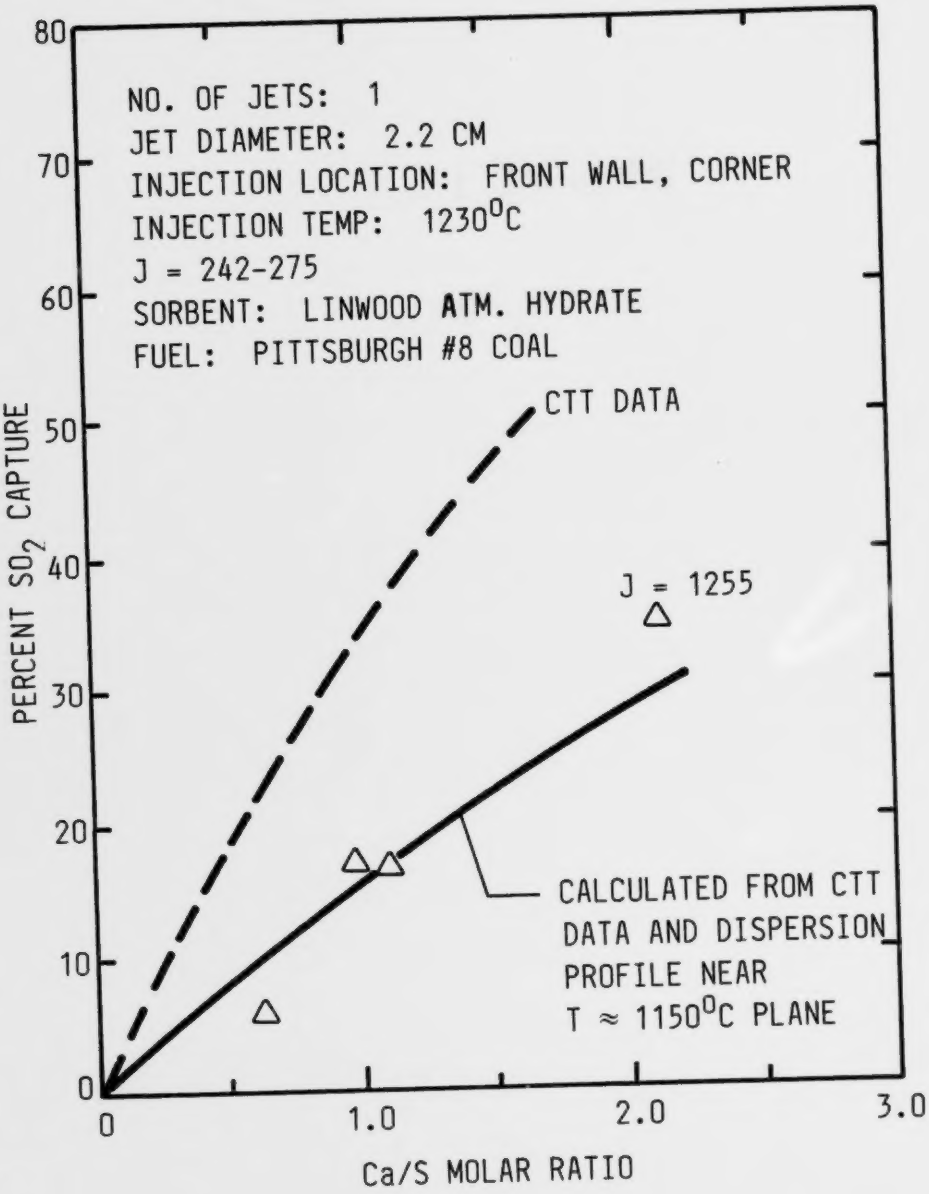


Figure 5-37. Predicted effect of dispersion on sulfur capture for one jet near corner at the nose plane.

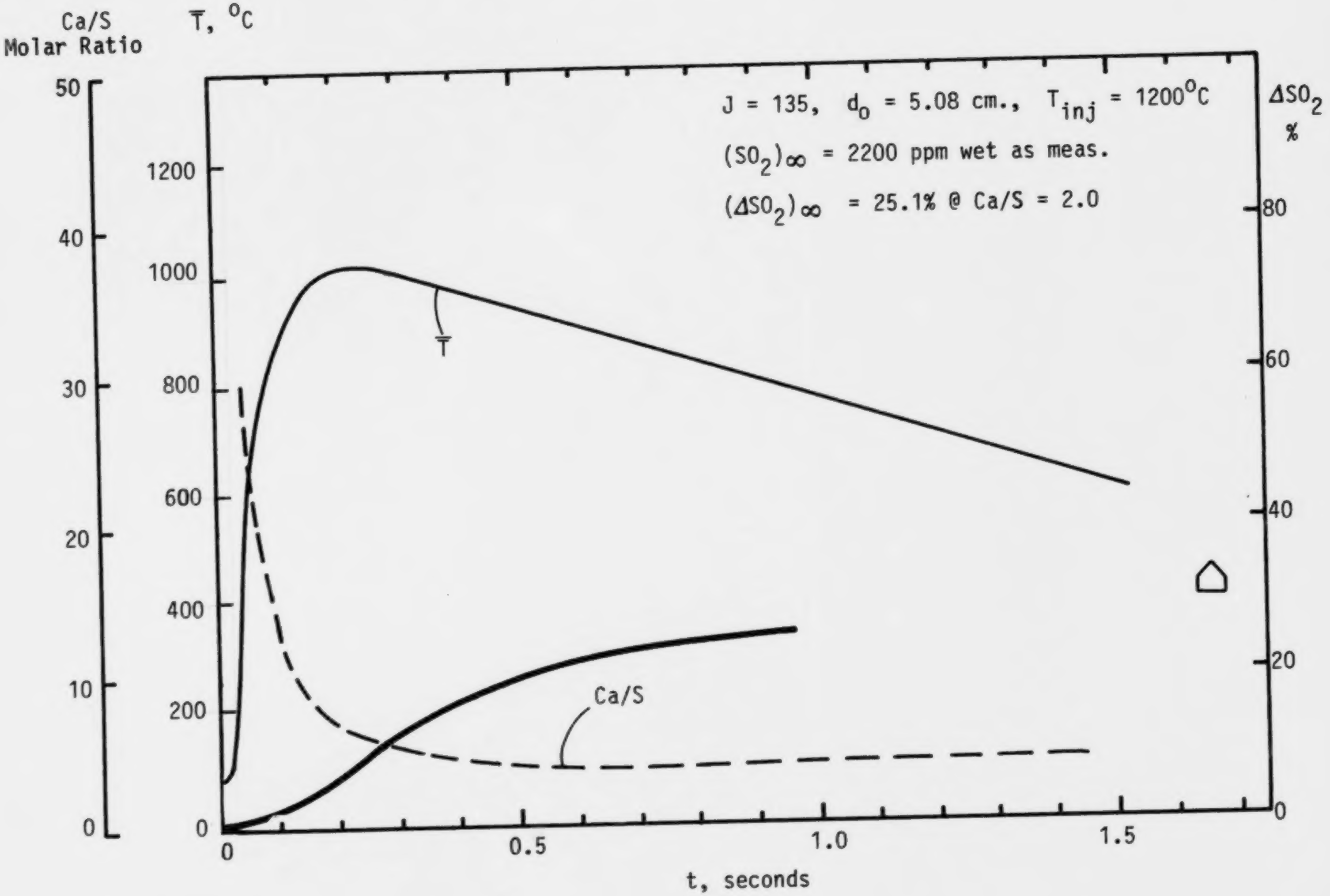


Figure 5-38. Computed effect of jet mixing on sulfur capture for one jet centrally injected on the front wall at the nose level.

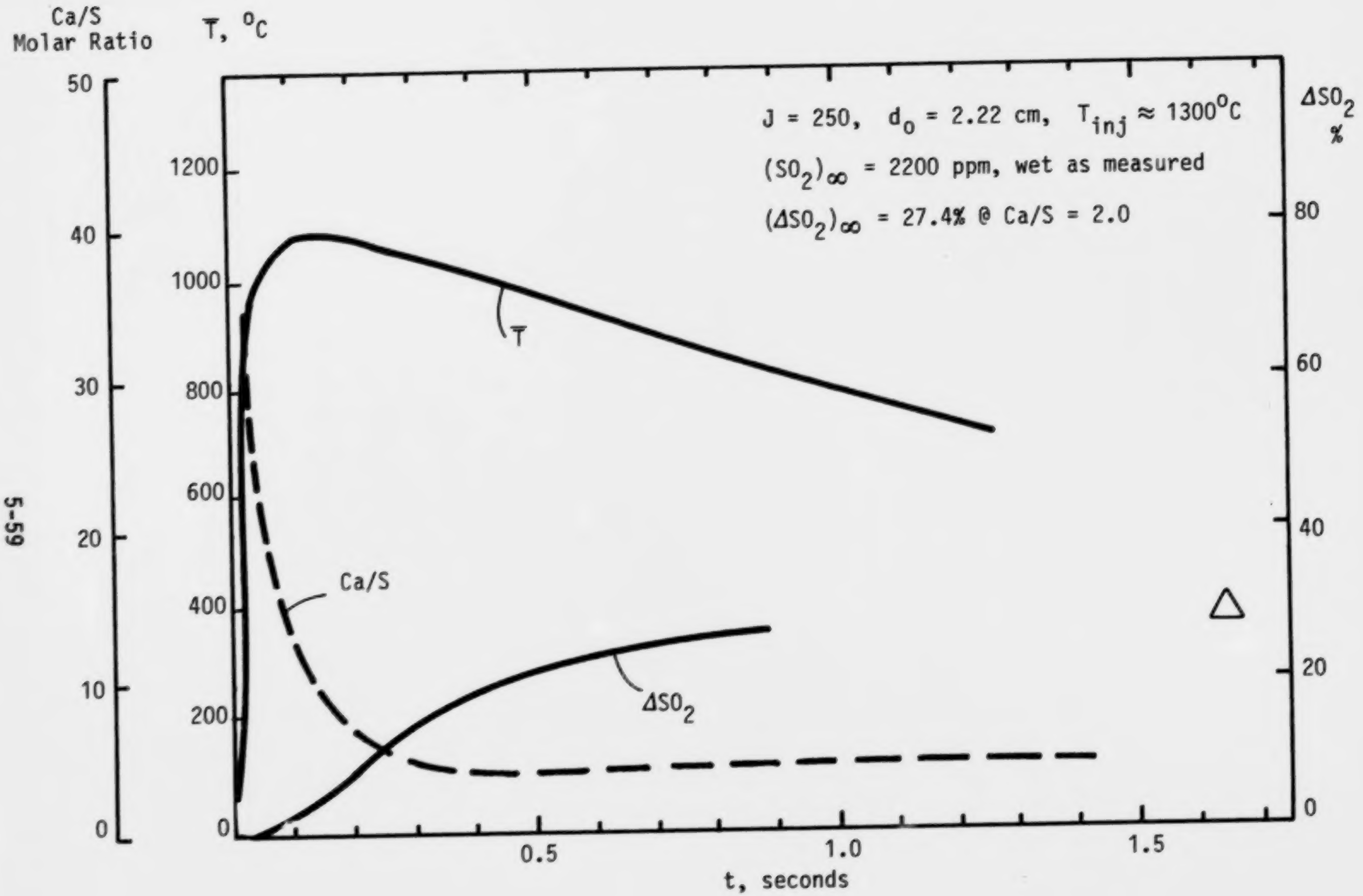


Figure 5-39. Computed effect of jet mixing on sulfur capture for one corner jet injected on the front wall at the nose level.

6.0 UPPER FURNACE SORBENT INJECTION IN THE LARGE WATERTUBE SIMULATOR (LWS) FURNACE

This section describes the upper furnace sorbent injection tests in the large Watertube Simulator (LWS) furnace at 24 MW_{th} (80 x 10^6 Btu/hr) firing rate. The main objective of these tests was to investigate the influence of sorbent injection parameters (jet nozzle configuration and location, nozzle size, injection velocity) on the sulfur capture at a large scale. The LWS furnace, used in this study, was designed to provide a simulation of a small utility boiler furnace for burner testing. In addition to its geometric similarity, LWS furnace was made thermally similar to a utility boiler furnace. Sorbents were injected in the upper furnace at temperatures near the beginning of sulfation temperature window, i.e. around 1230°C (2250°F) The sorbent injection nozzles were simple and double-concentric jets placed on the front wall of the combustor. The primary measure of the influence of injection parameters was the SO_2 reduction in the flue gas.

In the following, the experimental systems are first described in Subsection 6.1. The sulfur captures measured under various injection conditions are discussed in Subsection 6.2. Interpretation of the test results based on the isothermal modeling studies of this furnace is given in Subsection 6.3.

6.1 Experimental Systems

Upper furnace sorbent injection tests were conducted in EPA's Large Watertube Boiler Simulator (LWS) test facility. The combustor and its combustion systems, sorbent injection systems and sampling/measurement systems and instrumentation are described in the following paragraphs.

6.1.1 Combustor Systems

The LWS furnace is shown in Figure 6-1 along with the sorbent injection locations investigated during these tests. The LWS is a full-scale model of a small wall-fired utility boiler, WIPCO's Pearl Station. The furnace has a

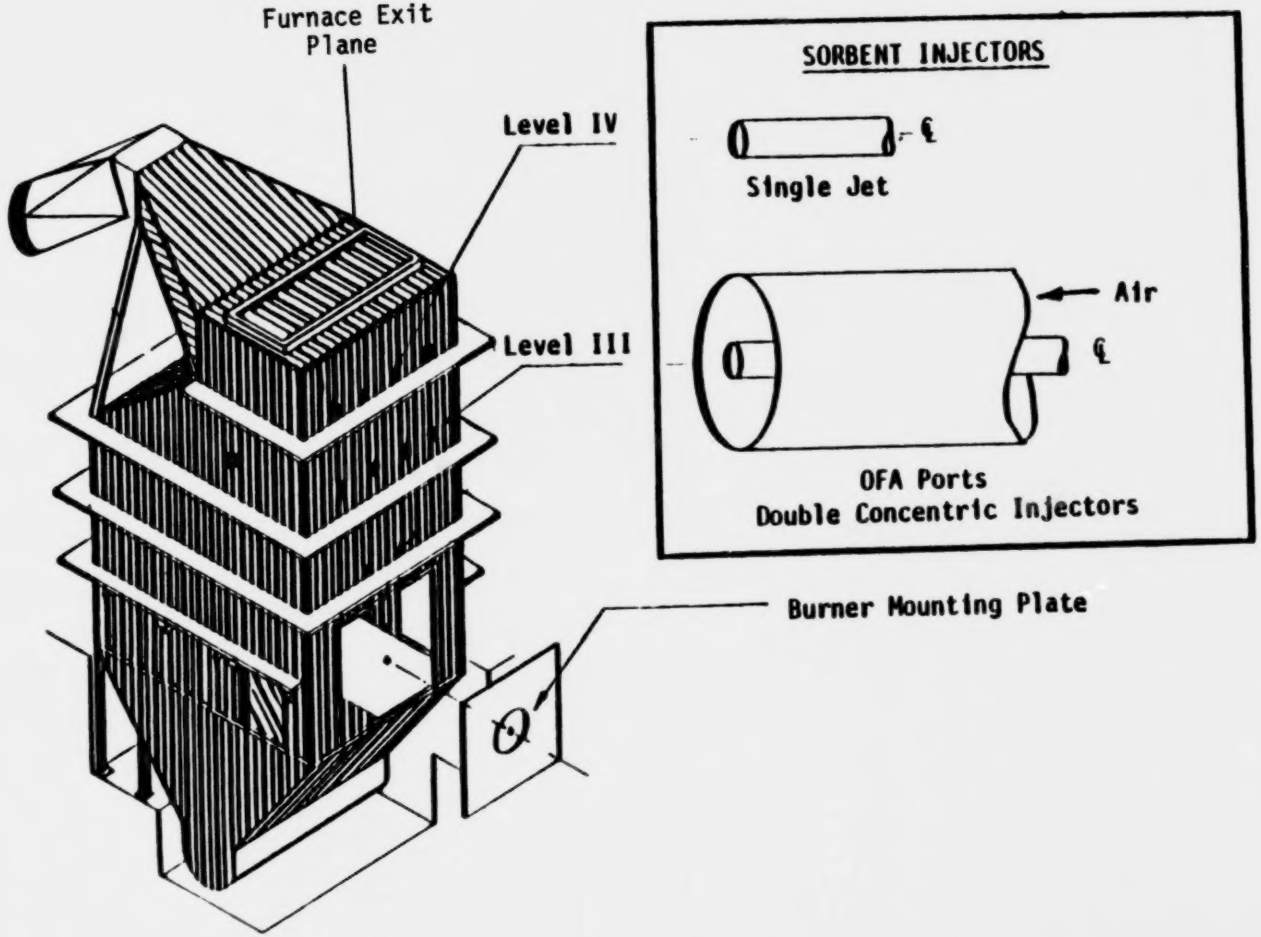

Furnace Exit Plane
Level IV
Level III
SORBENT INJECTORS
℄
Single Jet
Air
℄
OFA Ports
Double Concentric Injectors
Burner Mounting Plate

Figure 6-1. LWS furnace and injection locations.

maximum firing capacity of 45 MW_{th} (150 x 10^6 Btu/hr) which is limited only by pulverizer capacity. The firing depth is 6.7 meters (22 feet) which is sufficient to handle burners at the maximum firing rate. It is arranged in a front wall firing configuration with a 3 x 3 meter (10 x 10 ft) water-cooled frame on which the burners are mounted. The burner used during this study was a 24 MW_{th} (80 x 10^6 Btu/hr) dual secondary passage staged mixing burner shown in Figure 6-2. This burner was optimized for NO_x emissions prior to sorbent injection studies under a different program. Furnace characteristics are tabulated in Table 6-1.

The LWS furnace is basically a steel enclosure which is partially refractory-lined on the inside and cooled by water sprays on the outside. This unique design allows removal of the appropriate amount of heat from the combustor surfaces by evaporation of the water sprayed onto the walls. In its baseline configuration, the furnace refractory lining extends from the hopper knuckle up to 4.9 meters (16 ft). This provides a furnace exit temperature (see Figure 6-1) of 1040°C (1900°F) when operating at 24 MW_{th} (80 x 10^6 Btu/hr). Under the same firing rate, some of the furnace characteristics are

- total furnace heat release per unit area (*) = 1.423 x 10^5 kW/m^2
- burner zone heat liberation rate = 3.94 x 10^2 kW/m^2
- heat release per total furnace volume (*) = 71.4 kW/m^3
- total furnace residence time = 8.0 seconds
- burner zone residence time = 3.9 seconds
- gas quench rate in upper furnace (baseline configuration) = 167°C/sec

Figure 6-3 summarizes the air and fuel systems associated with the LWS furnace. Combustion air is supplied by a forced-draft blower through a tubular heat exchanger into a manifold. The combustion air flow rate is measured and controlled by multiple venturi flow meters and dampers. For

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(*) 1 kW/m^2 = 317 $Btu/hr\text{-}ft^2$, 1 kW/m^3 = 96.6 $Btu/hr\text{-}ft^3$

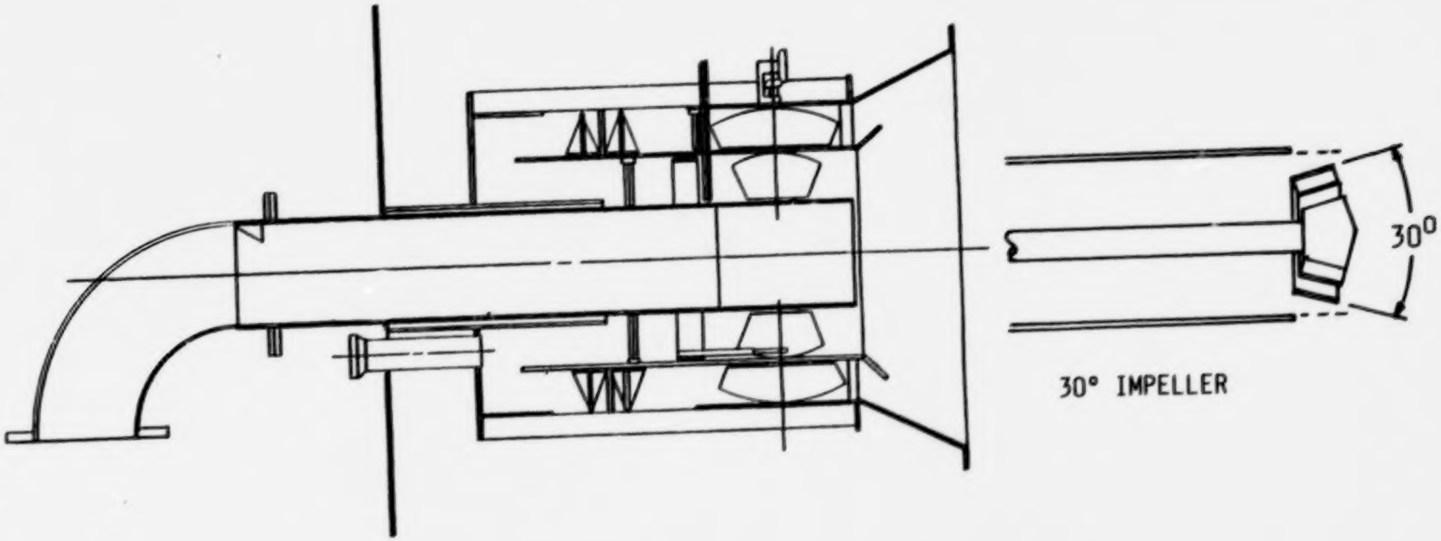

30°
30° IMPELLER

Figure 6-2. Optimized 24 MW_{th} (80 x 10^6Btu/hr) burner used during the sorbent injection tests.

TABLE 6-1. LWS FURNACE CHARACTERISTICS

Parameter		Value
Firing		
Configuration	Primary	Single Wall
	Optional	Opposed or Corner
Firing Rate	Minimum	50 x 10^6 Btu/hr (Practical Limit)
	Maximum	150 x 10^6 Btu/hr
Dimensions		
Firing depth		22 ft.
Width		16 ft.
Rear Wall Height		20 ft.
Knuckle to Nose Height		27.5 ft.
Nose Angle		37^o (from Horizontal)
Hopper Angle		52^o (from Horizontal)
Height Above Ground Level		35.7 ft.
Total Vertical Height		50.5 ft (Pit to Top)
Cooled Surface Area		
Burner Zone		704 ft^2
Total Furnace		1951 ft^2
Volume		
Burner Zone		3520 ft^3
Total Furnace		11,544 ft^3 (to Nose)
Insulation		All Sidewalls Knuckle-up to Nose
Cooling		Spray Cooled on All Surfaces

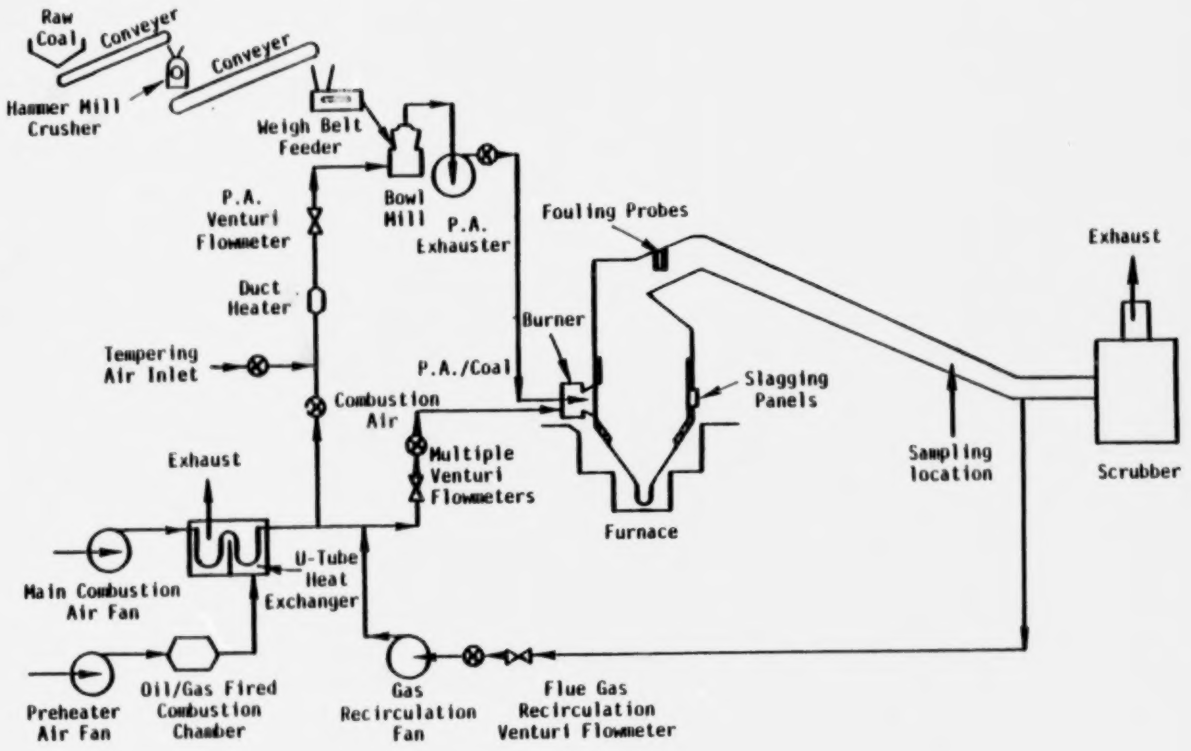

Raw
Coal
Conveyer
Hammer Mill
Crusher
Conveyer
Weigh Belt
Feeder
Bowl
Mill
P.A.
Exhauster
P.A.
Venturi
Flowmeter
Duct
Heater
Tempering
Air Inlet
Combustion
Air
P.A./Coal
Burner
Fouling Probes
Slagging
Panels
Furnace
Multiple
Venturi
Flowmeters
Exhaust
Main Combustion
Air Fan
U-Tube
Heat
Exchanger
Preheater
Air Fan
Oil/Gas Fired
Combustion
Chamber
Gas
Recirculation
Fan
Flue Gas
Recirculation
Venturi Flowmeter
Sampling
location
Exhaust
Scrubber

Figure 6-3. Large Watertube Boiler simulator system schematic.

burners equipped with a common windbox, several venturis allow accurate flow rate measurement over a wide flow rate range. The other side of the heat exchanger is supplied with hot exhaust gas from a separate natural gas/oil fired combustion chamber. This allows the combustion air preheat temperature to be controlled independently of the performance of the burner firing in the research furnace. In preparation for firing, the raw coal is crushed in a hammer mill followed by pulverization in a Raymond bowl mill. Coal flow rate is measured by a weigh-feeder. Primary air is taken from the main combustion air flow, with addition of tempering air from a duct heater for temperature control. Air flow rate is measured by a venturi flowmeter.

The furnace exhaust system is designed to permit a wide range of emission measurements. The main exhaust sampling is near the end of a long straight duct meeting EPA specifications for a minimum number of sampling points. Multiple sample points are available at this location, for simultaneous sampling for gaseous species, SO_2 and particulate. The temperature at the sampling point is about 540°C (1000°F). The exhaust duct is externally spray-cooled like the furnace. Downstream of the sampling location, the exhaust gas passes into a wet scrubber which controls particulate and SO_x emissions.

Several modifications were made to the furnace in order to more closely match the thermal characteristics of a typical utility boiler furnace. These modifications were aimed to obtain

- bulk furnace gas temperature of 1230°C (2250°F) at the nose plane
- bulk gas quench rate of 330°C/sec (600°F/sec) in the sulfation window (upper furnace) which is typical of large utility boilers
- flow patterns similar to those in the upper furnace of wall-fired utility boilers

The thermal modifications were aided by a three-dimensional heat transfer modeling of the LWS furnace. Heat transfer model was run at different furnace insulation conditions at a thermal input of 24 MW_{th} (80 x 10^6 Btu/hr). From this analysis, the insulation pattern and extent were determined to achieve a gas temperature of 1230°C at the nose level in the furnace. The temperature profile at the furnace exit was further tailored by a bank of cooling tubes (shown in Figure 6-4) to achieve a gas quench rate of approximately 360°C/sec (650°F/sec) Figure 6-5 shows the predicted and measured bulk gas temperatures as a function of residence time from the furnace exit plane (defined as the vertical plane shown in Figure 6-1). Based on measurements and predictions, a nominal gas quench rate of 360°C (650°F/sec) was obtained. Other modifications to the furnace included addition of six division panels as flow straighteners simulating superheater pendants, and a boundary layer trip on the back wall to tailor the flow field. At the beginning of the sorbent injection tests, the LWS furnace was used as an isothermal model where ash was introduced into the sorbent jets at various elevations on the front wall and jet penetration was observed visually. Figure 6-6 shows the flow field characteristics before the modifications and the smoke trajectories of jets in the small-scale isothermal model. The same behavior was observed in both the LWS and the small-scale model, where jets on the front wall below the nose plane were mostly drawn down towards the flame zone. Flow field studies indicated the presence of a large recirculation zone above the burners caused by the entrainment requirement of the high velocity burner jet. In order to alter the flow patterns and to help closing the recirculation zone below the nose at the front wall, a back wall boundary layer trip was introduced. The step on the back wall was shown to help close the recirculation zone on the front wall by creating a recirculation zone near the back wall contraction region as shown in Figure 6-7.

6.1.2 Sorbent Injection Systems

The sorbent injection system, shown in Figure 6-8, consisted of a feeder, hopper and air injection system. The feeder was a commercial weighbelt feeder similar to the one used to feed coal onto the mill. The air injection system included an air compressor, a venturi flowmeter to monitor carrier air flow and an ejector. The dry sorbent powder passed from the

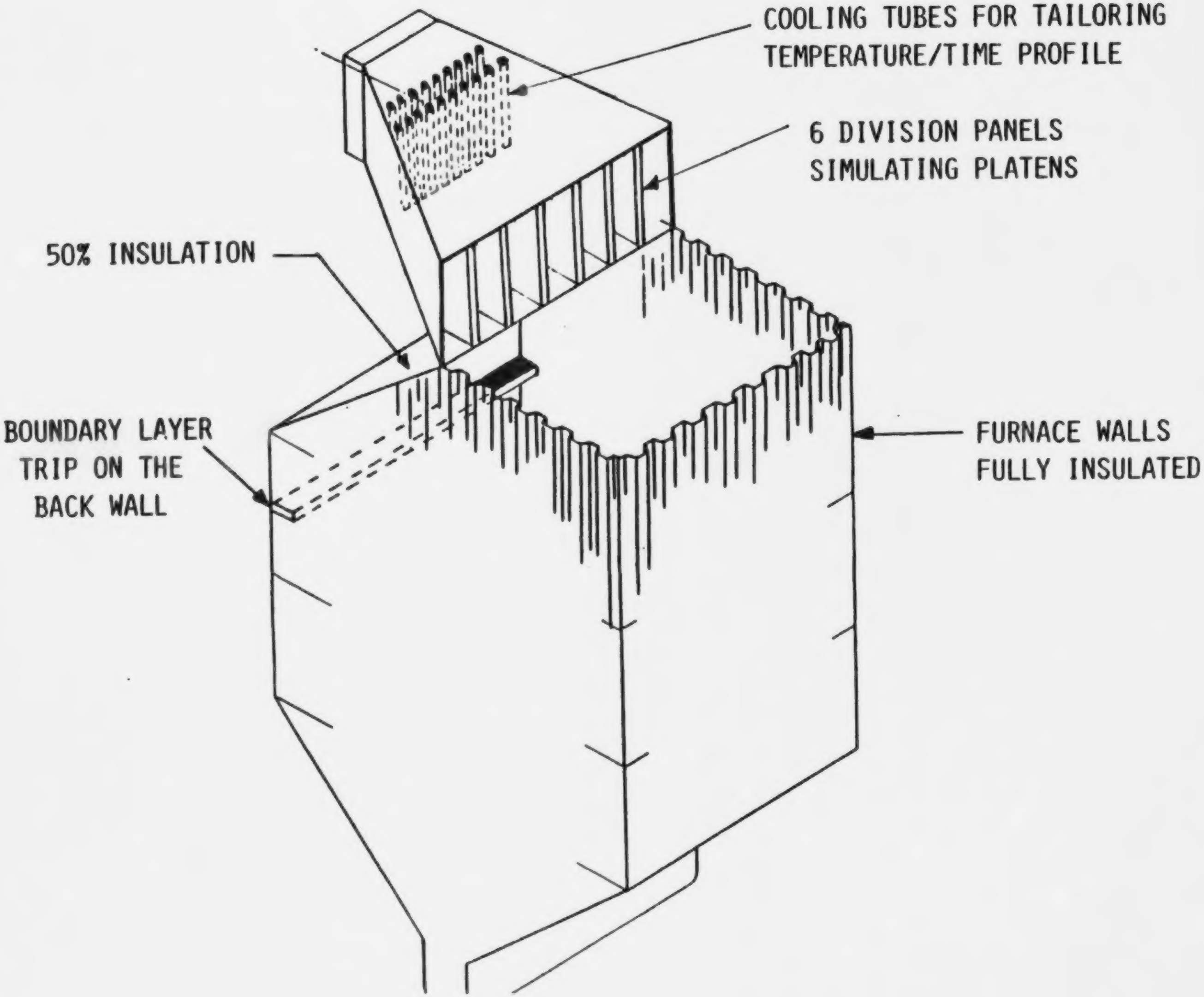

COOLING TUBES FOR TAILORING TEMPERATURE/TIME PROFILE
6 DIVISION PANELS SIMULATING PLATENS
50% INSULATION
BOUNDARY LAYER TRIP ON THE BACK WALL
FURNACE WALLS FULLY INSULATED

Figure 6-4. LWS furnace modifications.

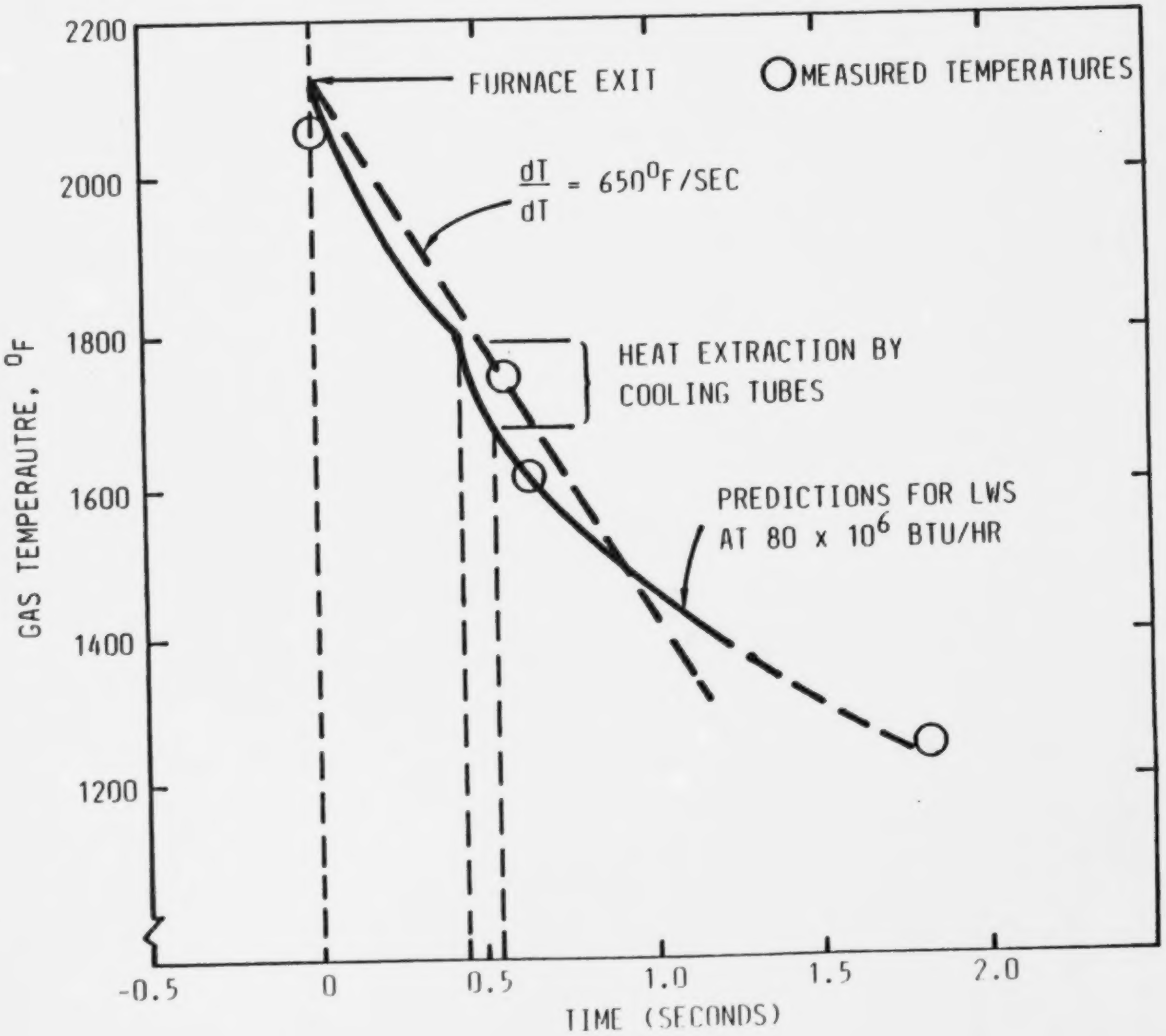


Figure 6-5. Temperature/time profile in the modified configuration of the LWS furnace.

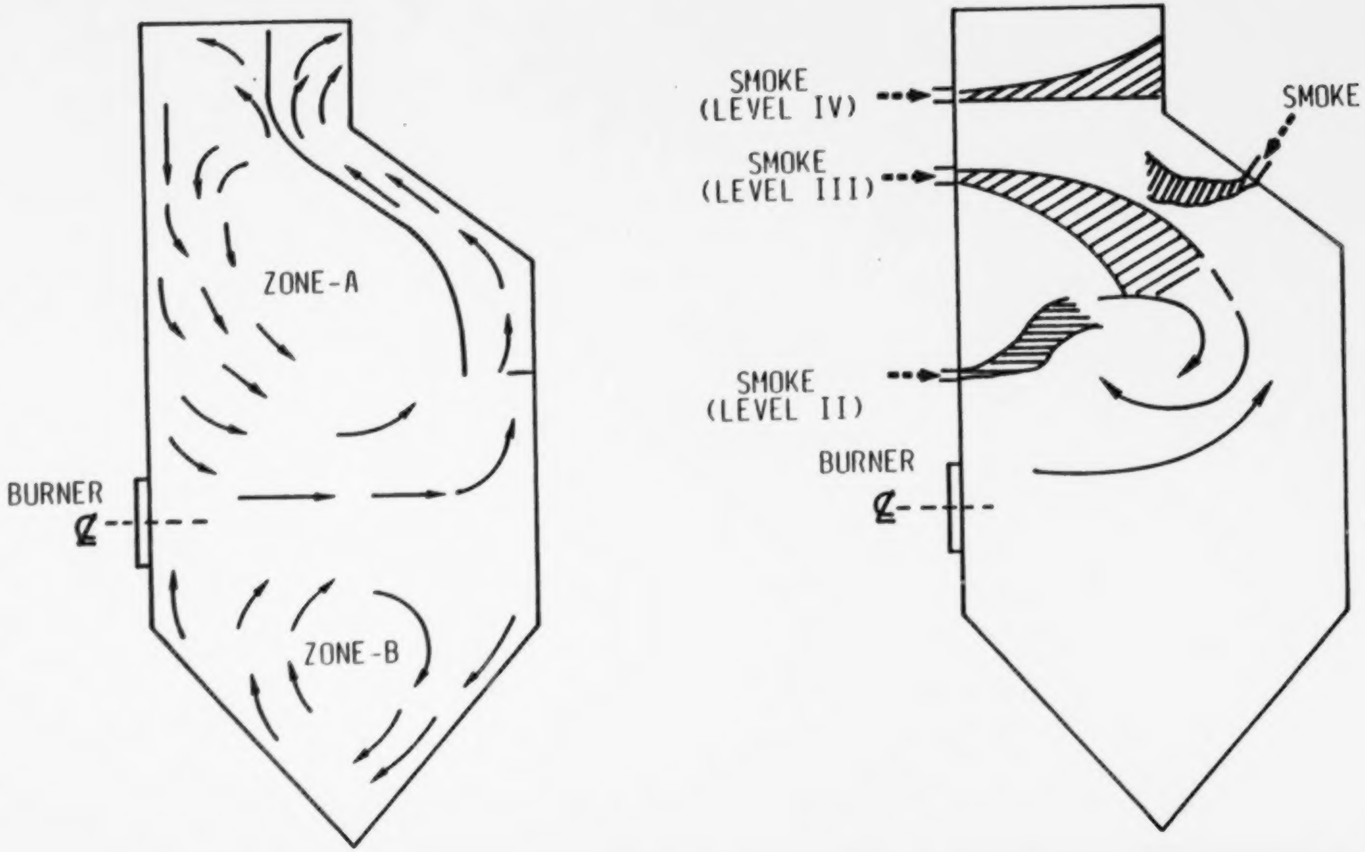

ZONE-A
BURNER
℄
ZONE-B
SMOKE (LEVEL IV)
SMOKE (LEVEL III)
SMOKE
SMOKE (LEVEL II)
BURNER
℄

Figure 6-6. Flow field characteristics before the modifications.

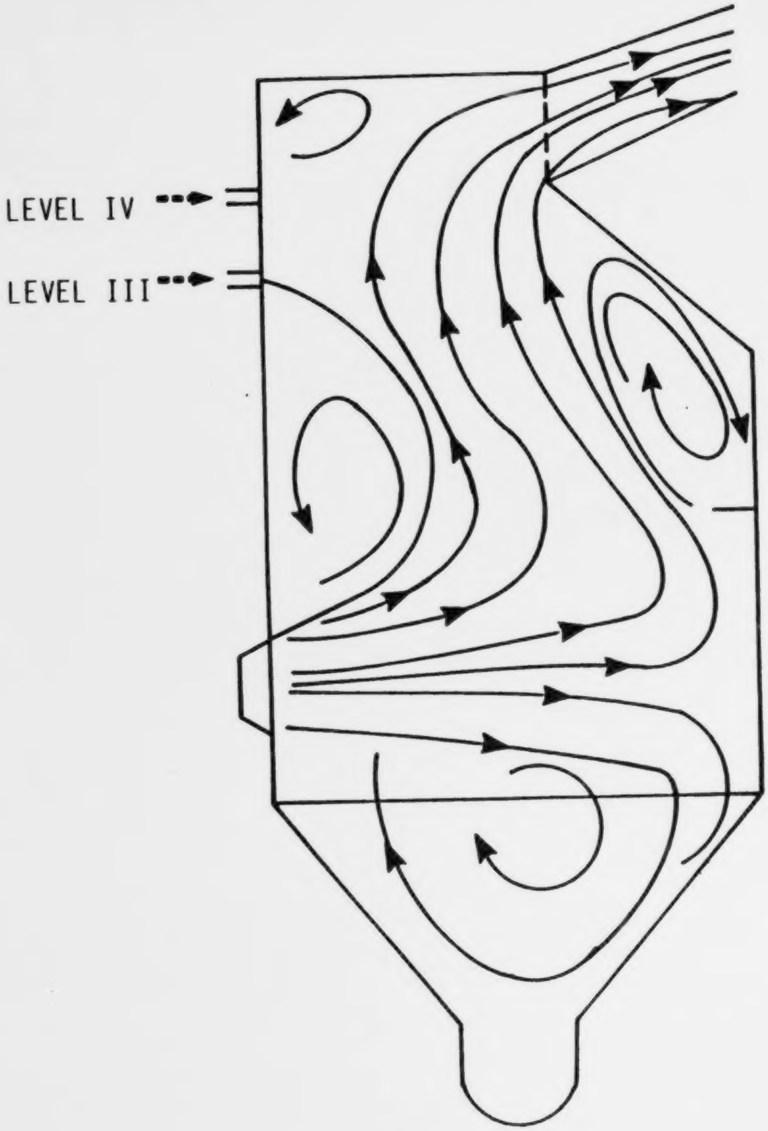

LEVEL IV
LEVEL III

Figure 6-7. Modified flow patterns with the addition of back wall boundary layer trip.

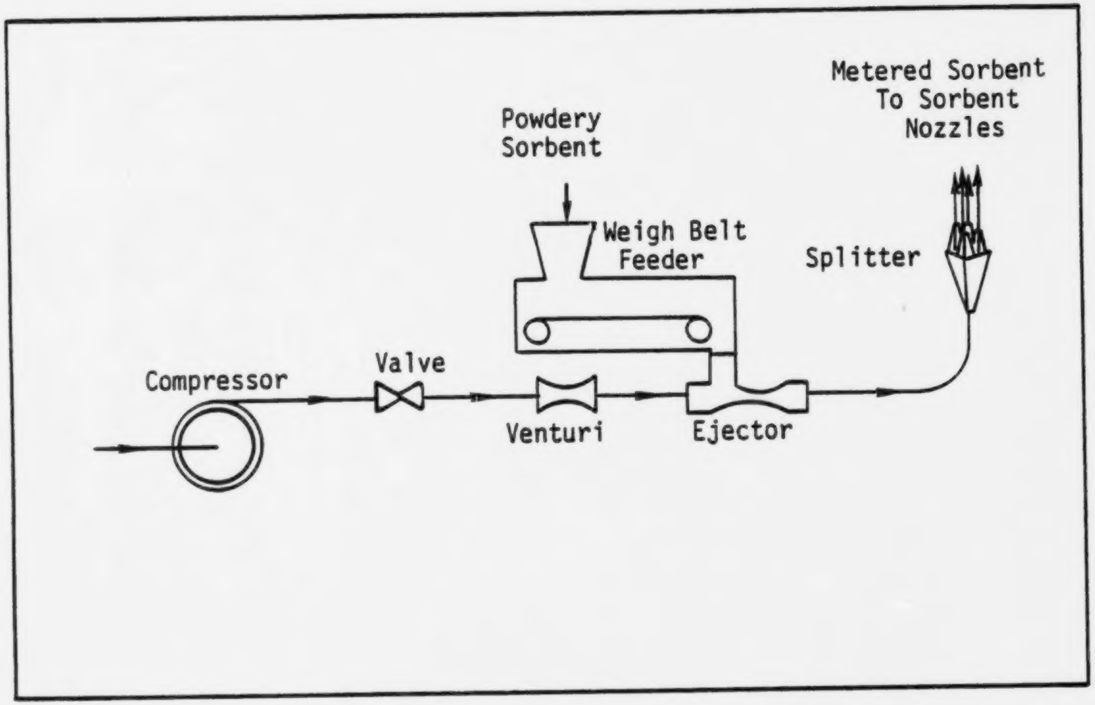

Metered Sorbent
To Sorbent
Nozzles
Powdery
Sorbent
Weigh Belt
Feeder
Splitter
Compressor
Valve
Venturi
Ejector

Figure 6-8. Diagram of sorbent feed system.

feeder hopper through the weigh feeder and into the ejector. The feeder's totalizer provided the actual sorbent mass flow rate, regulated by the feeder controller according to the preset value of mass flow. As an additional measure to verify independently the actual mass flow, direct feedrate was determined by sorbent weight-loss over time during each injection test.

The metered sorbent was entrained by the carrier air in the ejector and carried to a flow splitter located close to the LWS, where the sorbent flow was divided into separate streams for delivery to the sorbent injectors. The pipes connecting the flow splitter with the sorbent injectors were made of equal length flexible pipes to ensure that the split was as even as possible.

During these tests, sorbents were injected in the upper furnace in the following configurations:

- Four 8.9 cm. diameter jets on the front wall at Level III and IV (see Figure 6-1).
- Four 4.4 cm. diameter jets on the front wall at Level III and IV.
- Two 8.9 cm. diameter jets on right side (facing burner wall) and two center jets at Level IV.
- Four double concentric jets d_i = 4.4 cm., d_o = 15.2 cm. at Level III.

6.1.3 Fuels and Sorbents

High volatile bituminous Pittsburgh #8 coal was fired as the test fuel. The coal was the same coal used during the reburning tower furnace tests described in Section 5.0. The coal analyses are repeated in Table 6-2 for convenience. The typical coal size distribution obtained during these tests is plotted in Figure 6-9. The coal grind was 70 percent less than 74 m (200 mesh) which is considered to be typical for firing high volatile bituminous coals.

TABLE 6-2. COAL ANALYSES

Analysis \ Sample Date		10-30-85*	11-8-85*	11-20-85*	11-20-85**
Proximate Analysis (Percent, Dry)					
Ash		12.50	13.29	11.86	12.44
Volatile Matter		34.51	35.62	37.90	36.17
Fixed Carbon		52.99	51.09	50.24	51.39
Moisture (As Received)		1.44	1.35	1.33	2.03
Ultimate Analysis (Percent, Dry)					
C		70.26	68.49	70.15	71.52
H		4.66	4.51	4.77	4.81
N		1.25	1.46	1.32	1.34
S		2.98	3.04	3.31	3.23
Ash		12.50	13.29	11.86	12.44
O		8.35	9.21	8.59	6.66
Higher Heating Value, MJ/kg		-	-	-	29.63
Fusion Temp.(^{o}C)	Oxid.	-	-	-	1467
	Redu.				1446

*EER Lab. Analysis
**Hazen Research Analysis

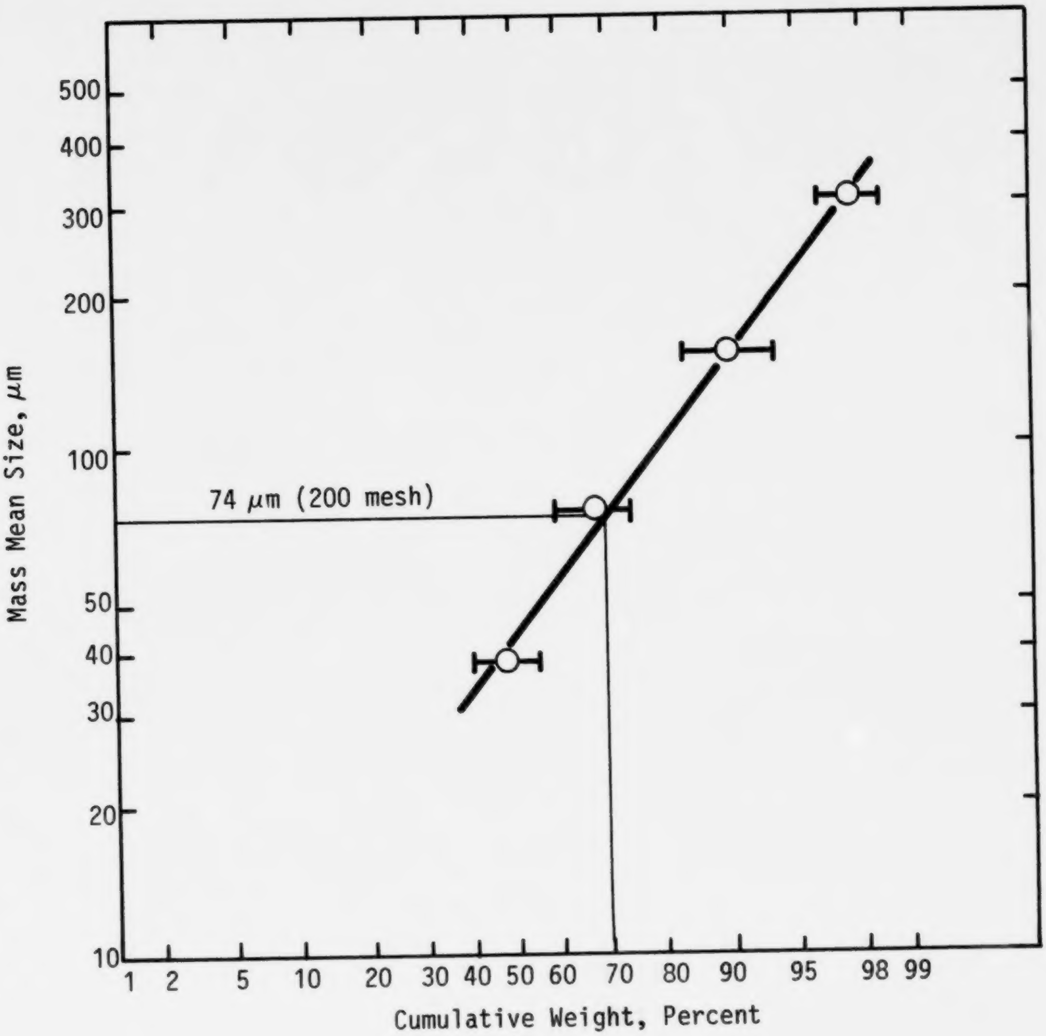


Figure 6-9. Coal size distribution during LWS tests.

Test sorbents were Linwood atmospheric hydrate ($Ca(OH)_2$), Vicron 45-3 ($CaCO_3$) and Colton atmospheric hydrate ($Ca(OH)_2$). Most of the tests were conducted with Linwood atmospheric hydrate which was also the baseline sorbent for the pilot scale tests discussed in Section 5.0. Only limited numbers of tests were done with Vicron limestone and Colton lime to study the comparative behavior of these sorbents with Linwood atmospheric hydrate. Some of the sorbent physical characteristics and chemical compositions are listed in Table 6-3. The sorbent particle size distributions are shown in Figure 6-10 for these three sorbents. The mass mean diameters of the sorbents were 2.0 μm, 4.0 μm and 10 μm for Linwood, Colton and Vicron, respectively.

6.1.4 Measurements and Instrumentation

The primary objective of these tests was to determine the influence of sorbent injection system parameters on the overall sulfur capture for several sorbents. This required measurement of gas phase sulfur species (mainly SO_2) at the furnace exhaust before and during sorbent injection under different injection conditions. This was the key characterization during these experiments. In addition, a detailed monitoring of all furnace input streams (fuel, air, sorbent) and exhaust emissions (CO, CO_2, NO_x, O_2) were performed. The analytical methods and instrumentation used in these studies are discussed in the following paragraphs.

The sampling train utilized for the continuous emission monitoring of the flue gas in the LWS facility is shown in Figure 6-11. All materials in contact with the sample are glass, 316 stainless steel or Teflon. These materials are non-reactive with NO at low temperatures. The stainless steel sampling probes are water-cooled, and small cyclones adjacent to the probe remove particulate matter and condensed water. The sample is then transported to the control room through a Teflon line where it is filtered and dried. The sample pump is Teflon lined and the sample flow rate is maintained at several times the instruments requirements to minimize response time. Excess sample flow is bypassed to a vent. Commercial gas analyzers are used for measurements of O_2, CO_2, CO, NO/NO_x and SO_2 and are listed in

TABLE 6-3. SORBENT CHARACTERISTICS

Sorbents Characteristics		Vicron ($CaCO_3$)	Colton Atmospheric Hydrate ($Ca(OH)_2$)	Linwood Atmospheric Hydrate ($Ca(OH)_2$)
Physical Properties	Mean Size (μm)	9.8	4.0	2.2
	Pore Volume (cm^3/g)	--	--	0.89
	Density (gm/cm^3)	2.71	2.27	2.30
	Surface Area (m^2/gm)	2	16.1	14.0
Chemical Analysis (Percent by Wt)	Ca	39.2	48.8	51.6
	Mg	0.33	0.48	0.97
	Na	0.007	0.02	0.004
	Si	0.09	0.35	0.66
	Al	0.02	0.10	0.18
	Fe	0.06	0.15	0.27
	C	11.90	--	0.33
	H	0.08	--	2.48
	N	--	--	0.04
	S	0.01	--	0.00

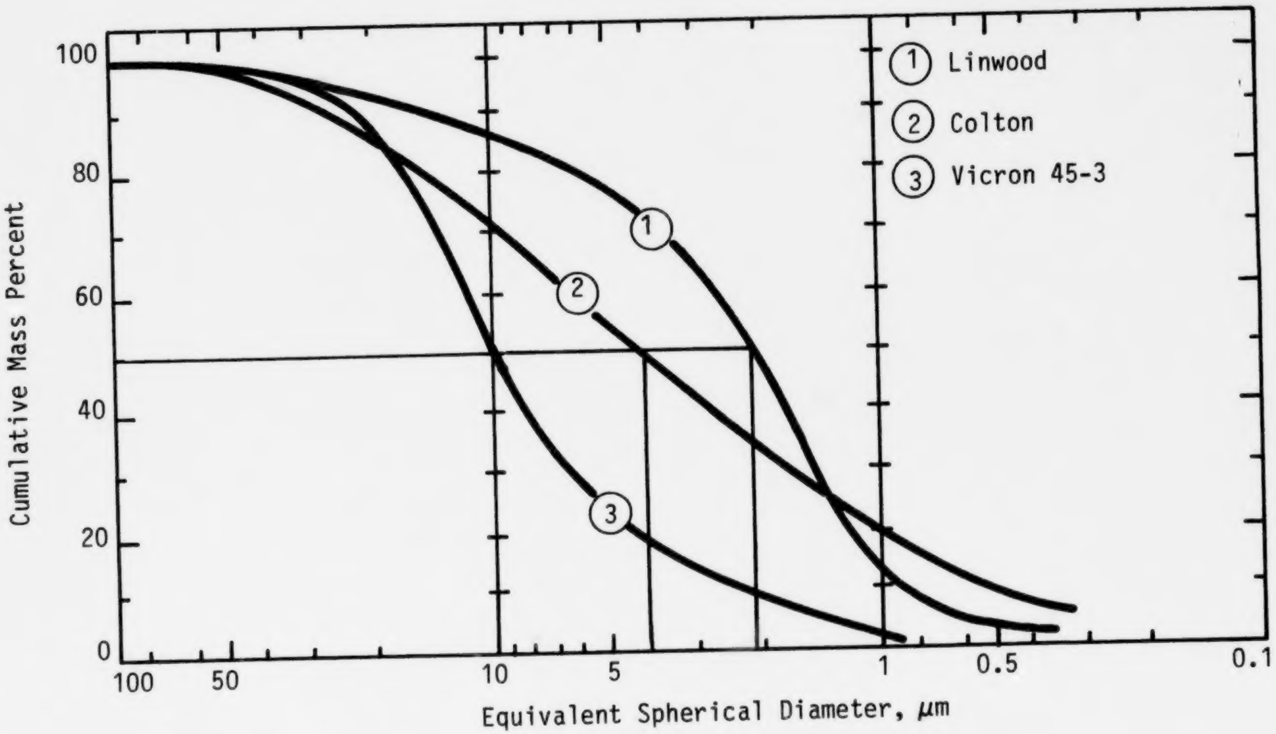


Figure 6-10. Particle size distributions of sorbents used during the tests.

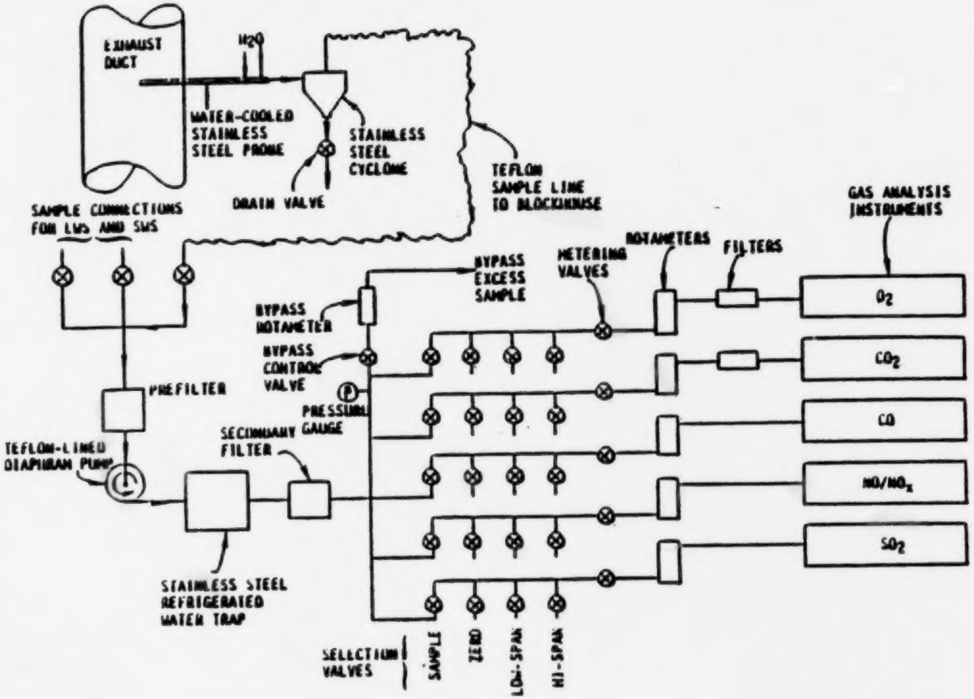

EXHAUST DUCT
H_2O
WATER-COOLED STAINLESS STEEL PROBE
STAINLESS STEEL CYCLONE
DRAIN VALVE
TEFLON SAMPLE LINE TO BLOCKHOUSE
SAMPLE CONNECTIONS FOR LWS AND SWS
PREFILTER
TEFLON-LINED DIAPHRAM PUMP
STAINLESS STEEL REFRIGERATED WATER TRAP
SECONDARY FILTER
PRESSURE GAUGE
BYPASS CONTROL VALVE
BYPASS ROTAMETER
BYPASS EXCESS SAMPLE
METERING VALVES
ROTAMETERS
FILTERS
GAS ANALYSIS INSTRUMENTS
O_2
CO_2
CO
NO/NO_x
SO_2
SELECTION VALVES
SAMPLE
ZERO
LOW-SPAN
HI-SPAN

Figure 6-11. Flue gas sample train schematic.

Table 6-4. The accuracy of each instrument is maintained by frequent calibration with zero and certified calibration gases.

Because of the inherent problems in measuring SO_2 concentrations in a stream with reactive sorbent particles, a separate sampling system was used during sorbent injection tests. This SO_2 sampling system is shown in Figure 6-12. A phase discrimination probe was used, which is designed to separate particulate matter from the sample gas that passes through the SO_2 analyzer. This separation prevents the SO_2 scrubbing effect which can take place in conventional filter probes when reactive sorbent is present. The sample passed through a heated sample line, into a heated filter, and into a commercial permeation tube dryer installed upstream of the instrument. The SO_2 measurement was therefore determined on a dry basis. The remaining central stream of the gas sample passed through a condenser and delivered a sample for the remaining instruments.

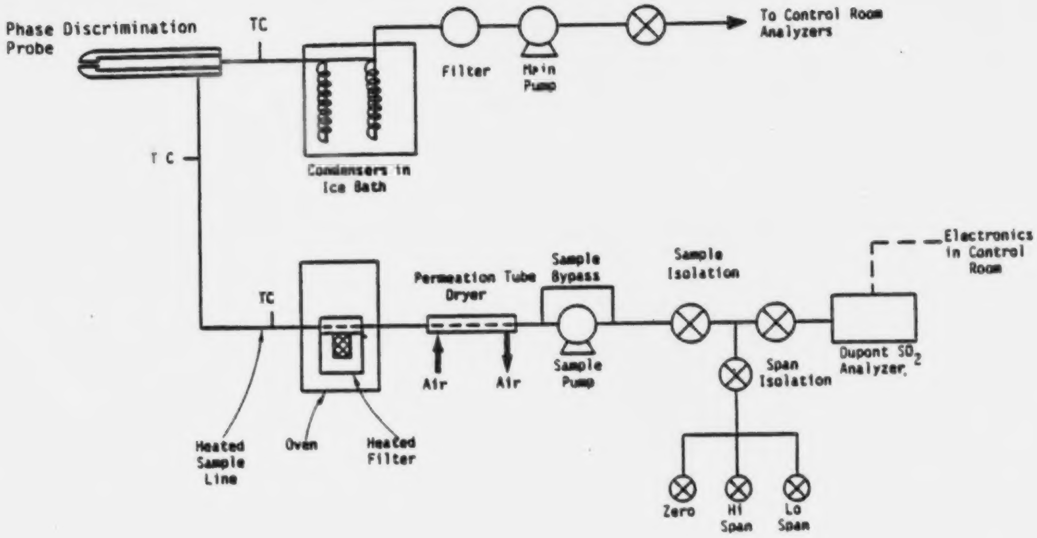
The electrical signals from the gas analyzers, venturis (through pressure transducers) and thermocouples were interfaced with a computerized on-line data acquisition system, and data were printed out in convenient engineering units. Those parameters which must be recorded manually (i.e. sorbent mass flow rate, windbox P, etc.) were entered into the microcomputer separately through a keyboard so that the computer generated data record was a complete listing of all parameters. Signals from the continuous emission monitors were logged directly onto a strip chart recorder.

In addition to continuous emissions monitoring, the following samples were collected for selected test conditions:

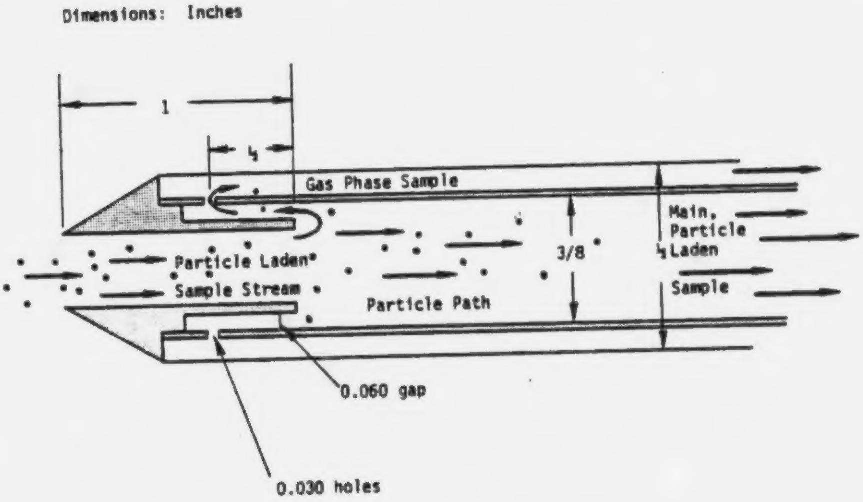
- EPA Method 6 (SO_2 sample)
- Pulverized coal samples (ASTM D197)
- Sorbent samples (Grab)

TABLE 6-4. GAS PHASE SPECIES INSTRUMENTATION

SPECIES	OPERATING PRINCIPLE	INSTRUMENT	MODEL NO.
O_2	Paramagnetic	Beckman	755
CO_2	Nondispersive Infrared	Anarad	AR-600
CO	Nondispersive Infrared	Anarad	AR-500R
NO/NO_x	Chemiluminescence	Teco	10R
SO_2	UV Absorption	DuPont	400


Phase Discrimination Probe
TC
Filter
Main Pump
To Control Room Analyzers
Condensers in Ice Bath
T C
Electronics in Control Room
TC
Permeation Tube Dryer
Sample Bypass
Sample Isolation
Air
Air
Sample Pump
Span Isolation
Dupont SO_2 Analyzer
Heated Sample Line
Oven
Heated Filter
Zero
Hi Span
Lo Span

a) Sampling System


Dimensions: Inches
1
¼
Gas Phase Sample
Main, Particle ¼ Laden Sample
3/8
Particle Laden Sample Stream
Particle Path
0.060 gap
0.030 holes

b) Phase Discrimination Probe

Figure 6-12. Schematic for sampling system for SO_2 concentration during sorbent injection tests.

6.1.5 Test Procedures

Established standard procedures were applied during the tests in accordance with the guidelines set by the Quality Assurance Project Plan (QAPP). Specific quality assurance activities are detailed in Appendix A. Standard measurement format was used for all tests except as indicated otherwise. The key input and output parameters measured during these tests are listed in Table 6-5.

6.2 Sorbent Injection Test Results

The sorbent injection tests were conducted with an optimized staged mixing burner operated under normal staged conditions at 24 MW_{th} (80×10^6 Btu/hr). Figure 6-13 shows the NO_x and CO emissions under optimized test conditions. A summary of the sorbent injection tests is given in Table 6-6. Many of the tests were conducted with Linwood atmospheric hydrate. The injection elevations and configurations are schematically shown in figure 6-14. The jet to cross flow momentum flux ratios are also listed in this table. At different Ca/S ratios corresponding to different sorbent feed rates, the jet velocities were adjusted to match the desired momentum flux ratios. In the following, the test results are presented and an interpretation of the results is given with the aid of isothermal modeling.

6.2.1 Effect of Jet Momentum

Tests were conducted with Linwood atmospheric hydrate injected through 9.8 cm. diameter simple jets at Level IV. The test results are shown in Figure 6-15. This figure shows two rather surprising results. These are:

- There was a significant impact of jet momentum on sulfur capture levels for this particular set of experiments.

- At high jet momentum, the capture levels were high (approximately 70 percent at Ca/S molar ratio of 2.0).

TABLE 6-5. STANDARD MEASUREMENT FORMAT

Input Parameters	Output Parameters
Burner Setting	Flame Characteristics
Combustion Air Flow Rate	Combustion Products: (Gas Phase)
Combustion Air Flow Temp.	- O_2
	- CO
Fuel Flowrate	- CO_2
	- NO_x
Sorbent Injection Location	- SO_2
Sorbent Flow Rate	Burner/Furnace Pressures
Sorbent Carrier Air Flow	Flue Exit Temperatures

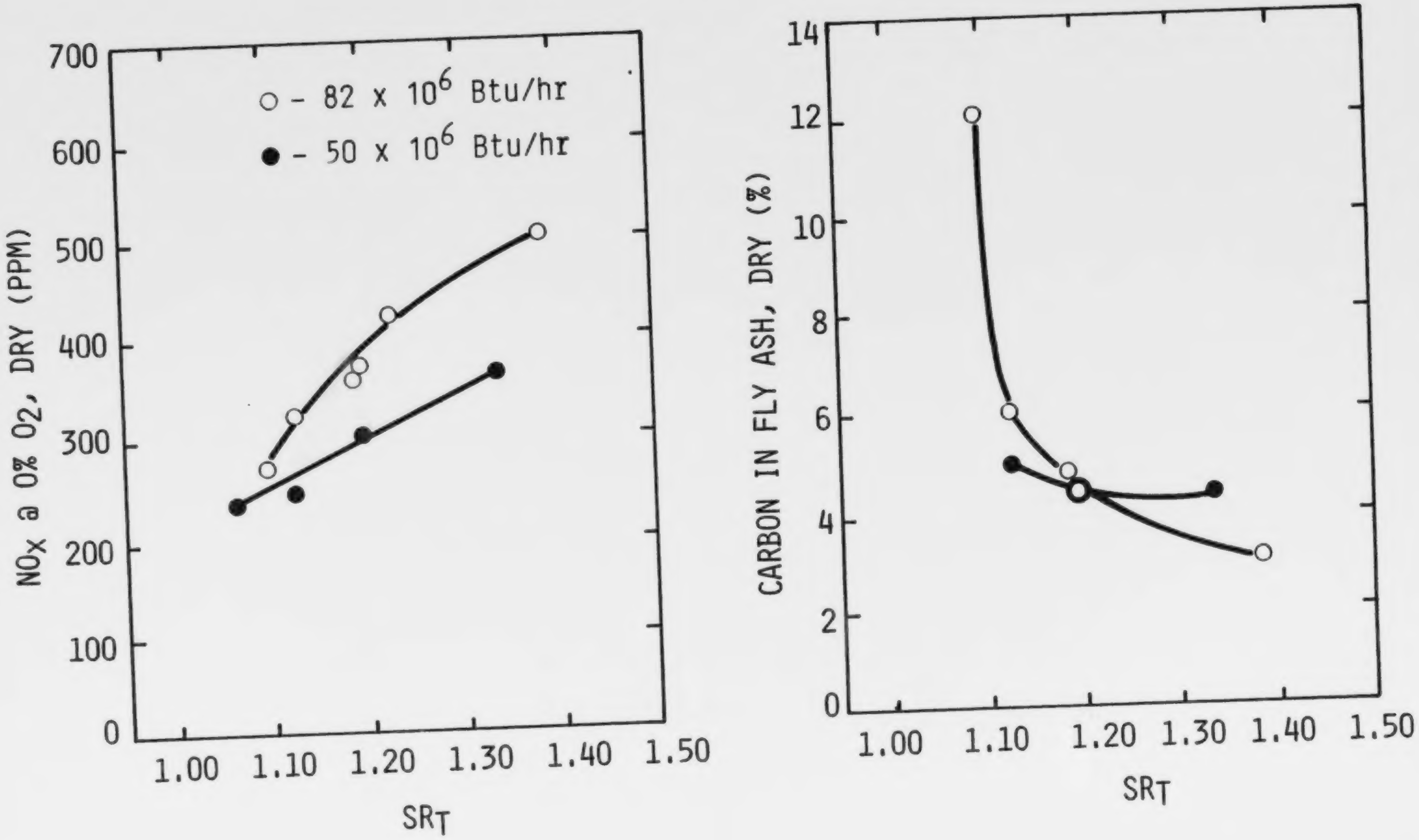


Figure 6-13. NO_x and CO emissions with the optimized XCL burner used during sorbent injection tests.

TABLE 6-6. SORBENT INJECTION TEST MATRIX

Sorbent	Injection Location	Injection Configuration	Injector Diameter, cm	Jet to Cross Flow Momentum J
Linwood	Level IV	A	8.9	50 150 200
Linwood	Level IV	A	4.4	500 1000
Linwood	Level IV	B	8.9	150
Linwood	Level IV	C	8.9	150
Linwood	Level III	A	8.9	50
Linwood	Level III	A	2.5	4640
Linwood	Level III	A	$\left\{ \begin{array}{l} d_i = 2.5 \\ d_o = 15.2 \end{array} \right\}$	3500 6586
Vicron	Level IV	A	8.9	50 150
Colton	Level IV	A	8.9	150 200

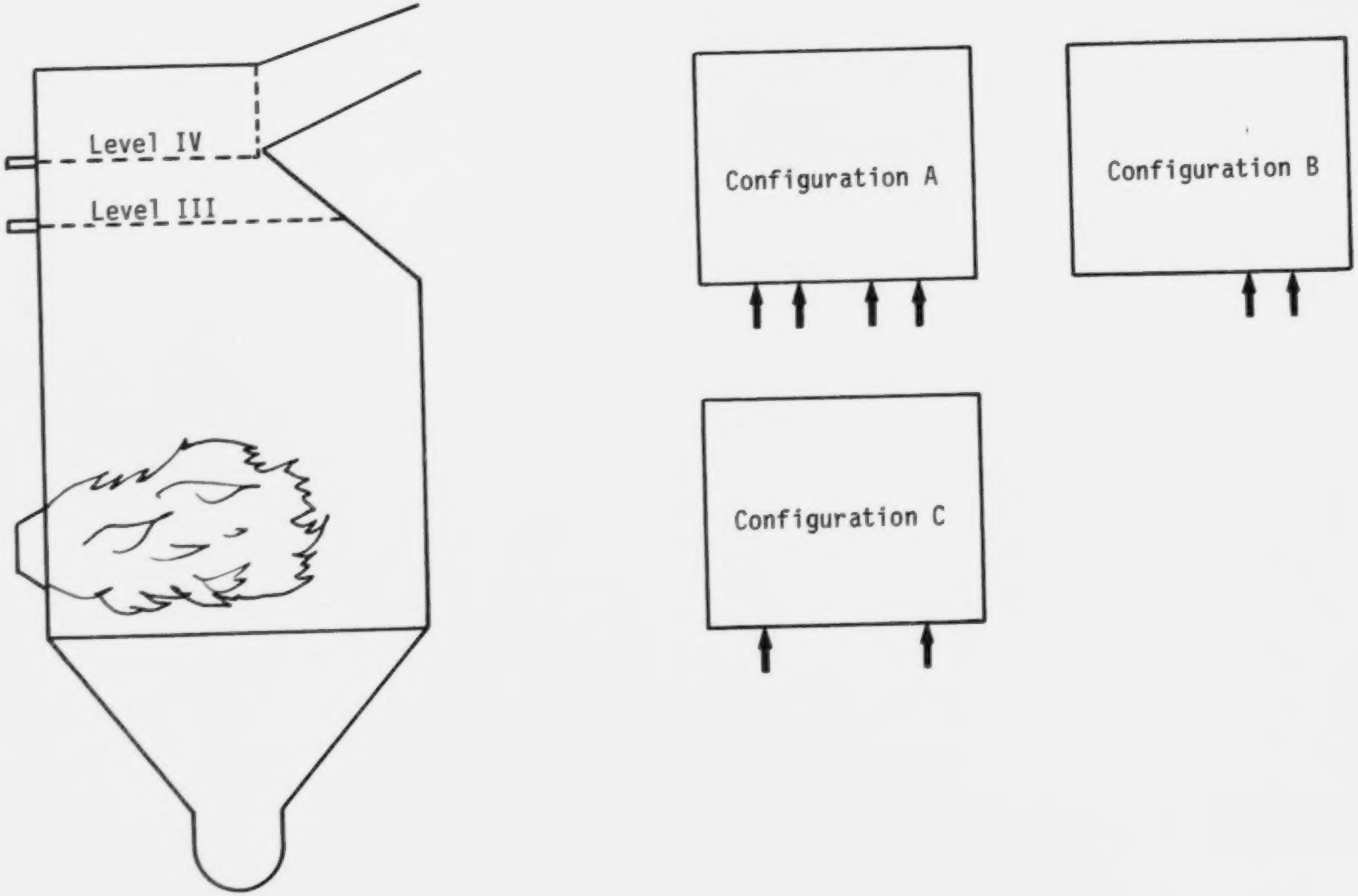

Level IV
Level III
Configuration A
Configuration B
Configuration C

Figure 6-14. Sorbent injection configurations in the LWS furnace.

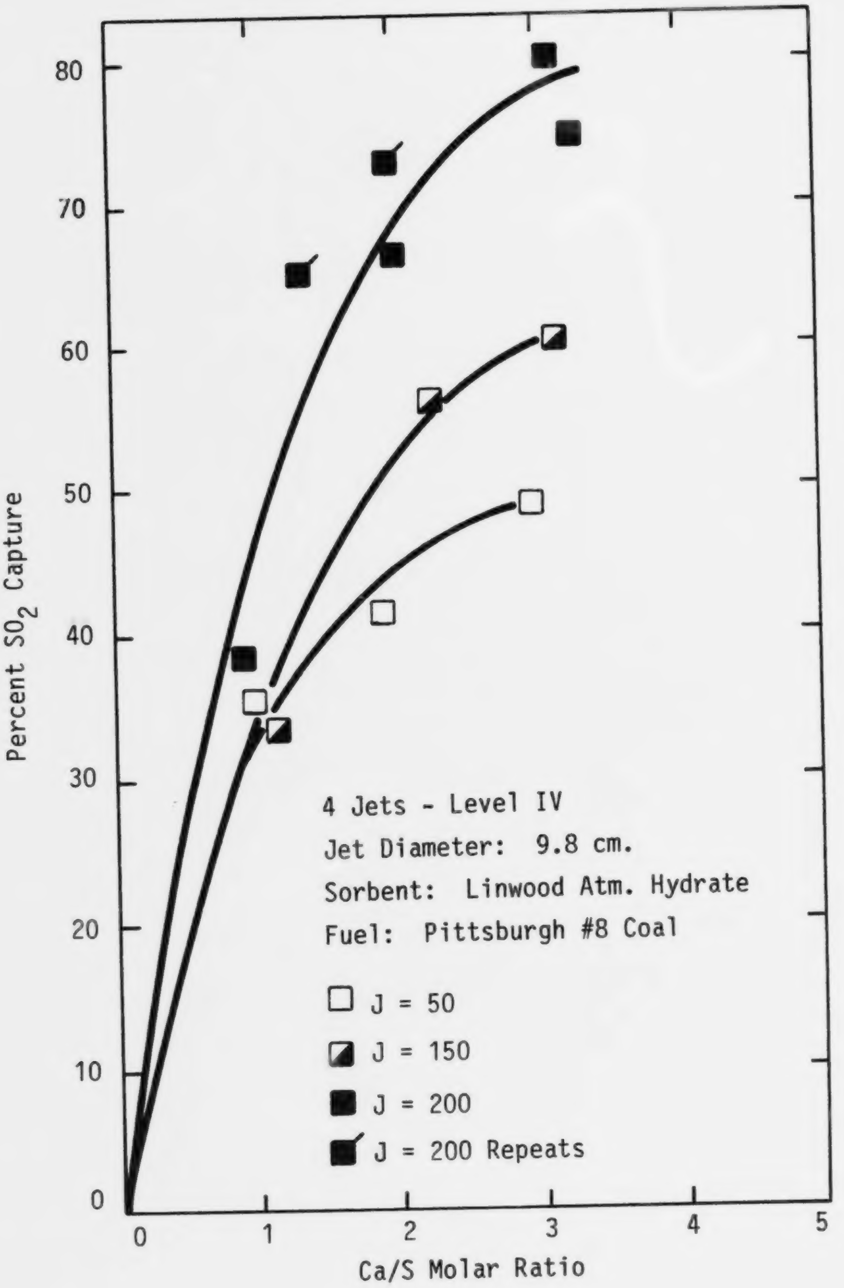


Figure 6-15. Effect of momentum flux ratio on sulfur capture with Linwood atmospheric hydrate at Level IV.

The first of these findings was contrary to the results obtained from the reburning tower furnace experiments. In order to ensure that these results were not anomalous, experiments at high momentum flux were repeated several different times during the test period and several months later during a short test. All test procedures and instrumentation were checked and no problems were identified. However, the analysis of solids did not give a confirmation of the high gas phase sulfur capture levels. In the past, the agreement between the gas phase captures and the corresponding solid phase captures was found to be poor especially for high sulfur capture cases. This is believed to be due to particle retention in the LWS furnace, the consequently non-representativeness of the solid samples.

In order to explain this rather strong dependence of sulfur capture on jet momentum, a semi-empirical/computational approach, similar to that described in Section 3.0, was taken. The flow field near the injection location was such that the jets experienced a relatively weak cross flow followed by the break-up of the jet due to the high velocity flue gas stream near the nose point. This observation allowed computations of bulk jet temperature and Ca/S molar ratio variations with time based on simple turbulent jet entrainment as shown in Figures 6-16, 6-17 and 6-18. In these calculations, the degree of mixing was linearly interpolated to perfect mixing between the furnace exit and the exhaust duct entrance. This was indicated by linear regions in the Ca/S curves. This assumption was made due to the rapid mixing of sorbent stream with the high velocity furnace flow stream at the furnace exit plane. The temperature-time and Ca/S-time variations provided the input conditions for the calcination/sulfation models in the manner described in Section 5.0. The sulfur capture levels are shown in Figure 6-16, 6-17 and 6-18. The key result from this exercise was that the sulfur capture ranged between 70 and 77 percent of Ca/S ratio of 2.0, regardless of the jet momentum. The capture levels were close to those measured in the LWS furnace. These results indicated that:

- high sulfur capture levels of about 70 percent at Ca/S ratio of 2.0 can be possible

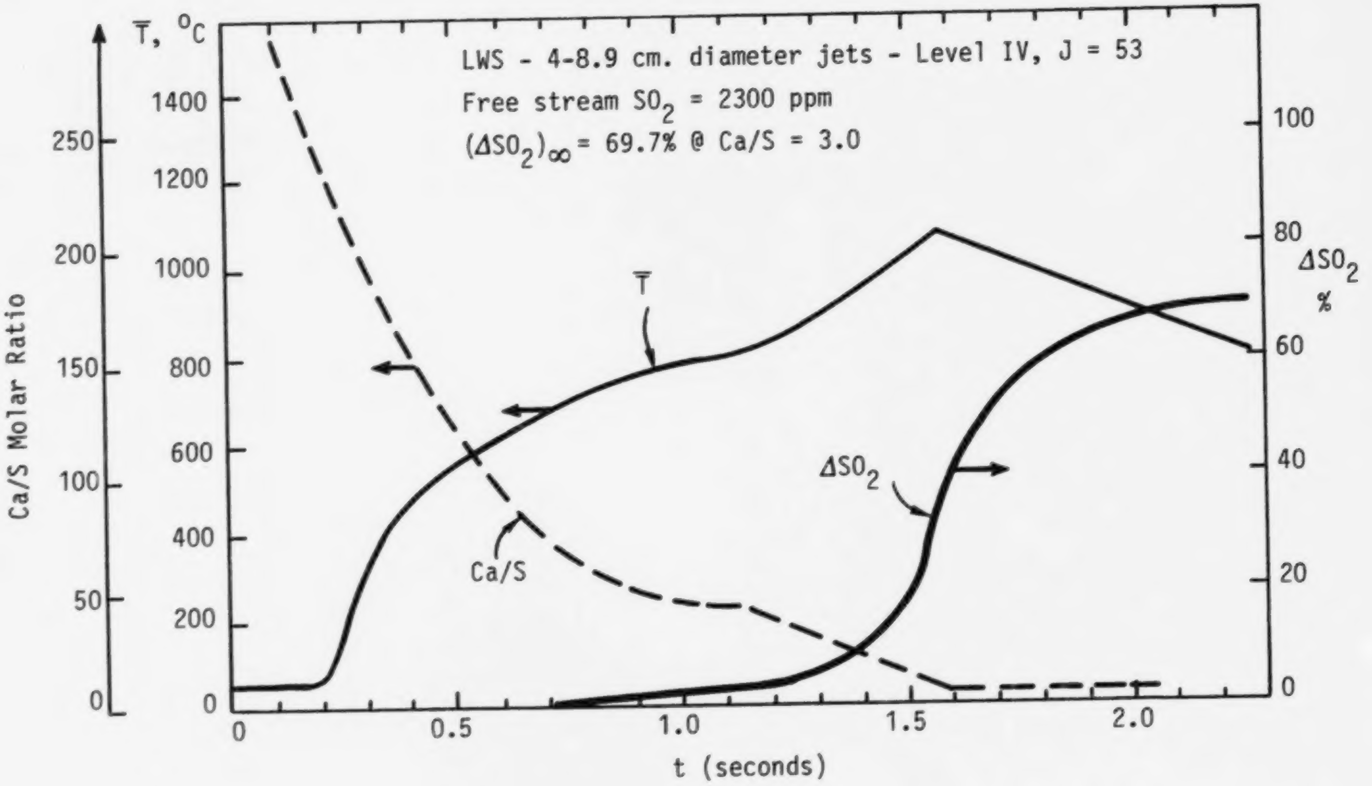


Figure 6-16. Predicted sulfur capture based on empirical jet mixing and computational calcination/sulfation models at a jet momentum flux ratio of 53.

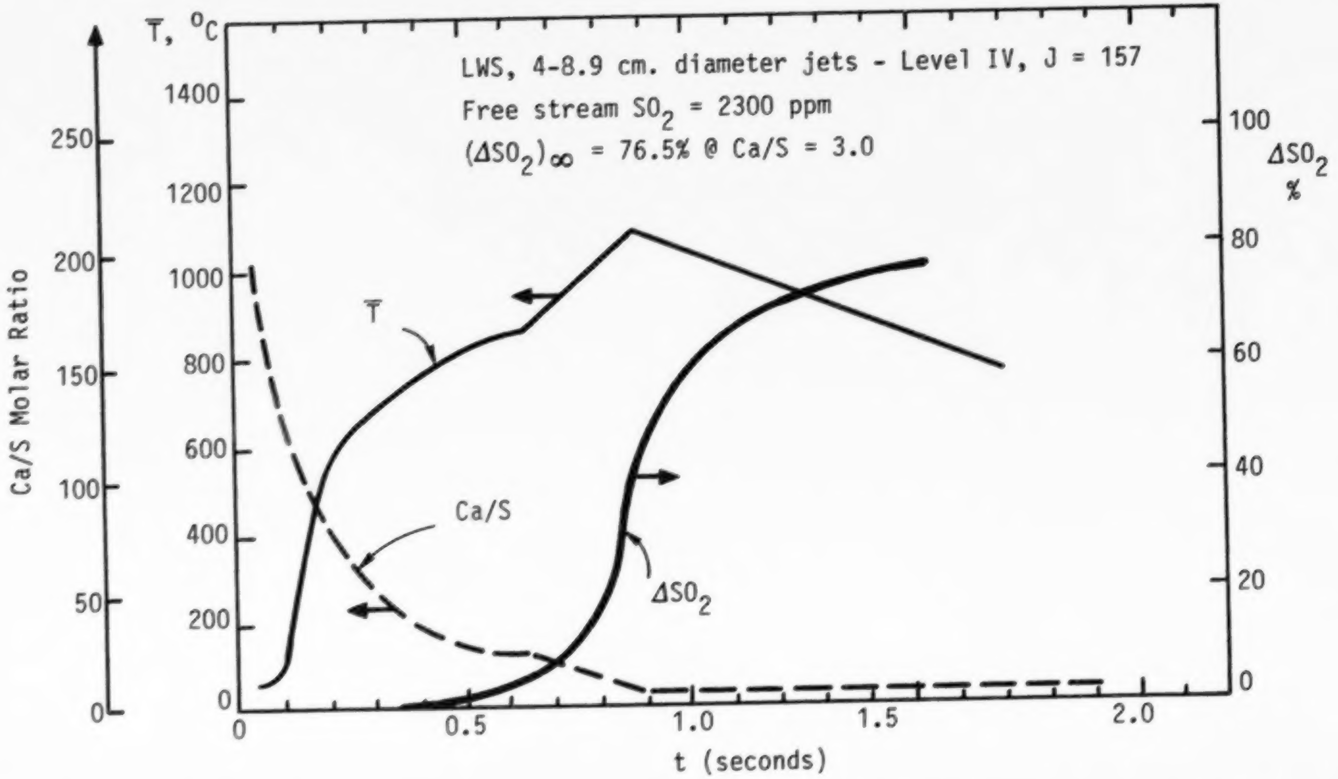


Figure 6-17. Predicted sulfur capture based on empirical jet mixing and computational calcination/sulfation models at a jet momentum flux ratio of 157.

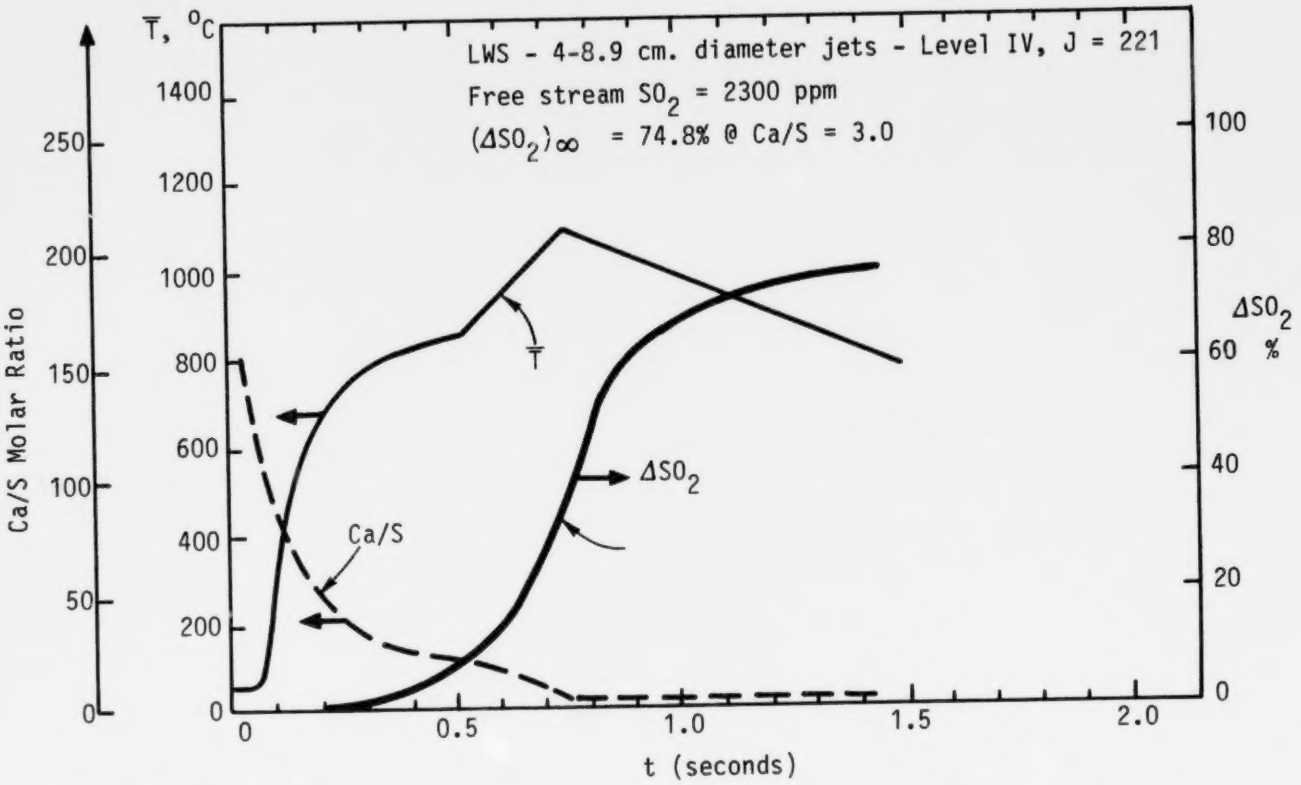


Figure 6-18. Predicted sulfur capture based on empirical jet mixing and computational calcination/sulfation models of a jet momentum flux ratio of 221.

- insensitivity of the sulfur capture to jet momentum alone points toward the fact that dispersion of the sorbent should be responsible for the differences in sulfur capture.

This prompted a series of isothermal tests in the 1/15 scale model of the LWS furnace and the LWS furnace itself. Both tests showed that some of the jet fluid was peeled off the jets and carried to the lower furnace within the large recirculation zone near the front wall. Observations of smoke injected through the jets in the small scale isothermal model and ash introduced into jets in the LWS operating as an isothermal model showed that the amount of jet fluid peeling off decreased as the jet momentum was increased. Figure 6-19 shows this behavior schematically. In the real situation, the part of the sorbent stream drawn into the lower furnace was probably exposed to high temperatures near the flame zone, thus dead burned. Contribution of this part of the sorbent stream can be assumed to be negligibly small to the overall sulfur capture. Therefore, as the jet momentum increased, more of the sorbent stream was utilized for sulfation which may have led to the results shown in Figure 6-15.

An attempt was made to quantify the fraction of the jet fluid drawn into the furnace and thereby interpreting the results of Figure 6-15. For this purpose, isothermal model of the LWS furnace was used to study the behavior of injection jets by tracer measurements. Jets were scaled for reproduction of the entrainment and penetration characteristics of the sorbent jets. Methane tracer measurements were conducted at two planes upstream and downstream of the injection point. Figures 6-20, 6-21 and 6-22 show the normalized tracer concentration profiles (normalized with respect to initial jet tracer concentration) for jet to cross flow momentum flux ratios of 50, 150 and 200 respectively. Here, the plug cross flow conditions at the upper nose cross section were used to calculate the momentum flux ratios.

Comparison of these figures indicate that more of the jet fluid was pulled down to the lower furnace at low jet momentum as initially conjectured. This effect was also reflected by the lower furnace exit tracer concentrations at the low momentum flux. A simple calculation method was

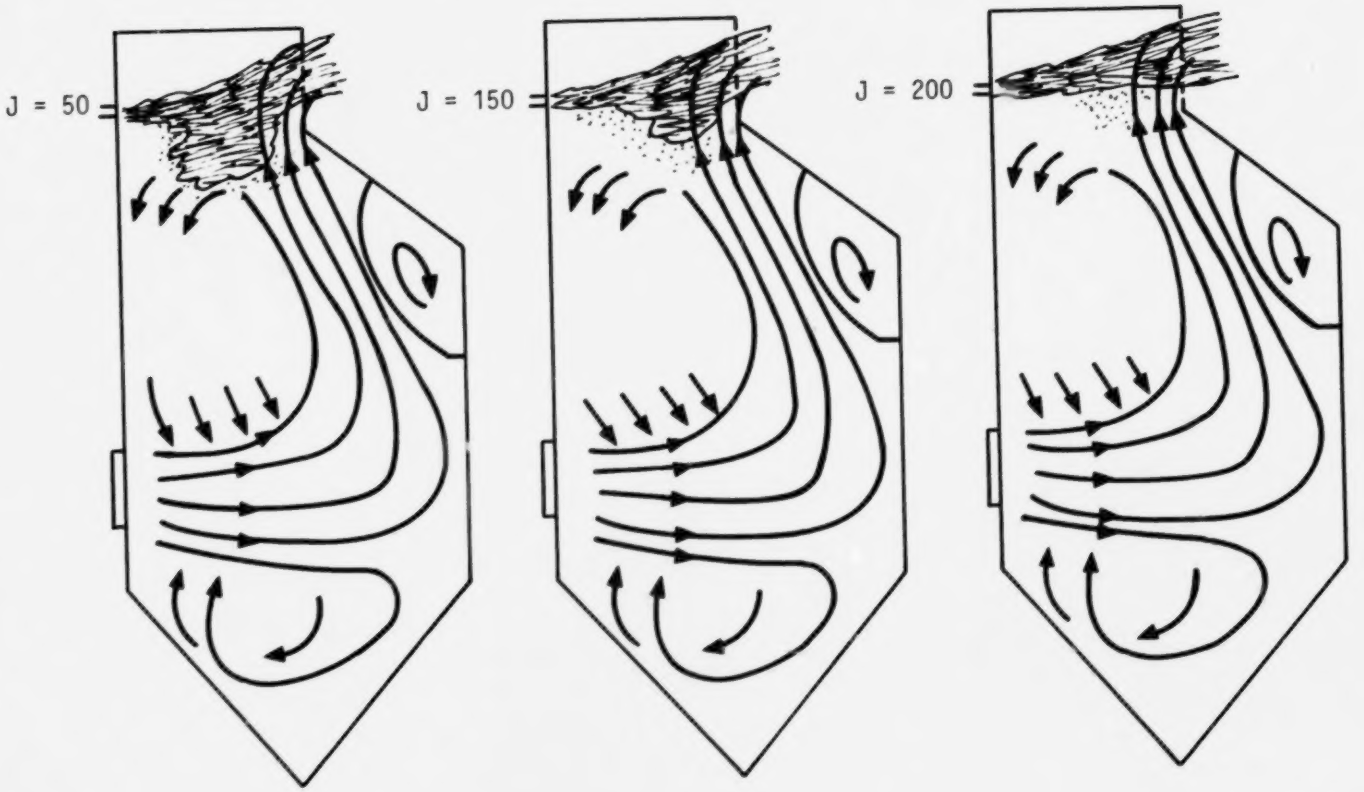

J = 50
J = 150
J = 200

Figure 6-19. Behavior of injection jets at level IV in the LWS furnace.

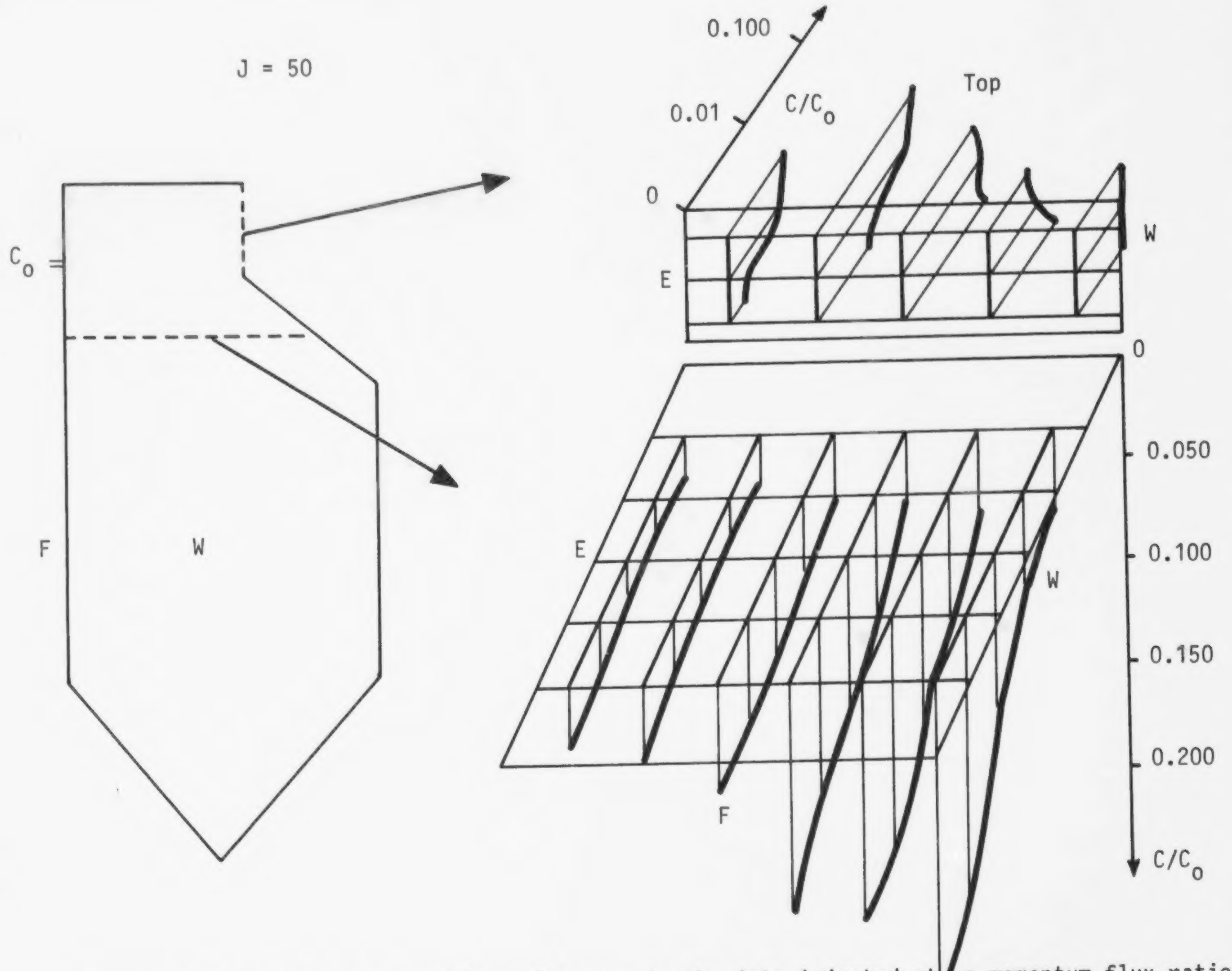


Figure 6-20. Dispersion profiles of tracer in the jets injected at a momentum flux ratio of 50 at Level IV in the isothermal model of LWS furnace.

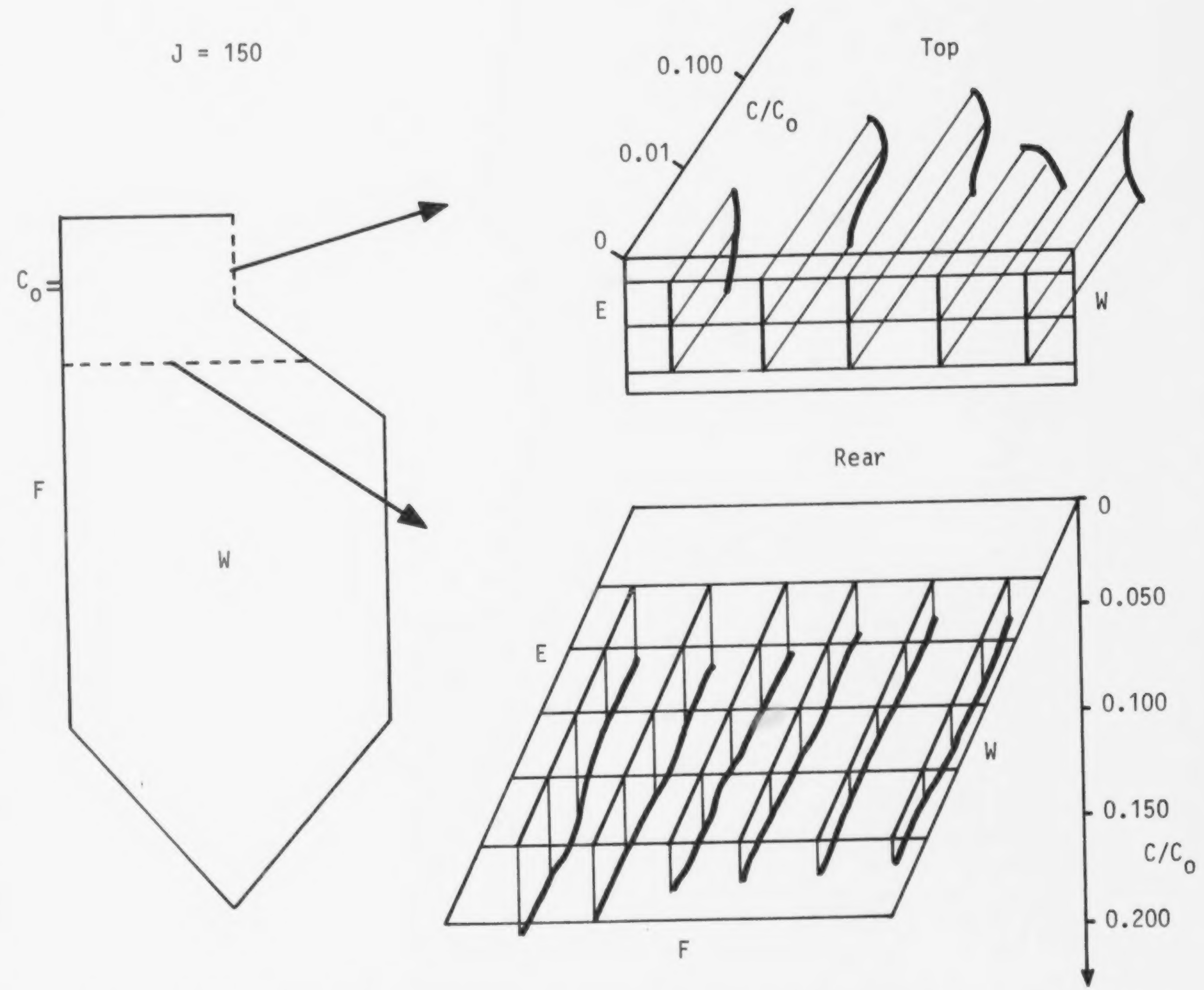


Figure 6-21. Dispersion profiles of tracer in the jets injected at a momentum flux ratio of 150 at Level IV in the isothermal model of LWS furnace.

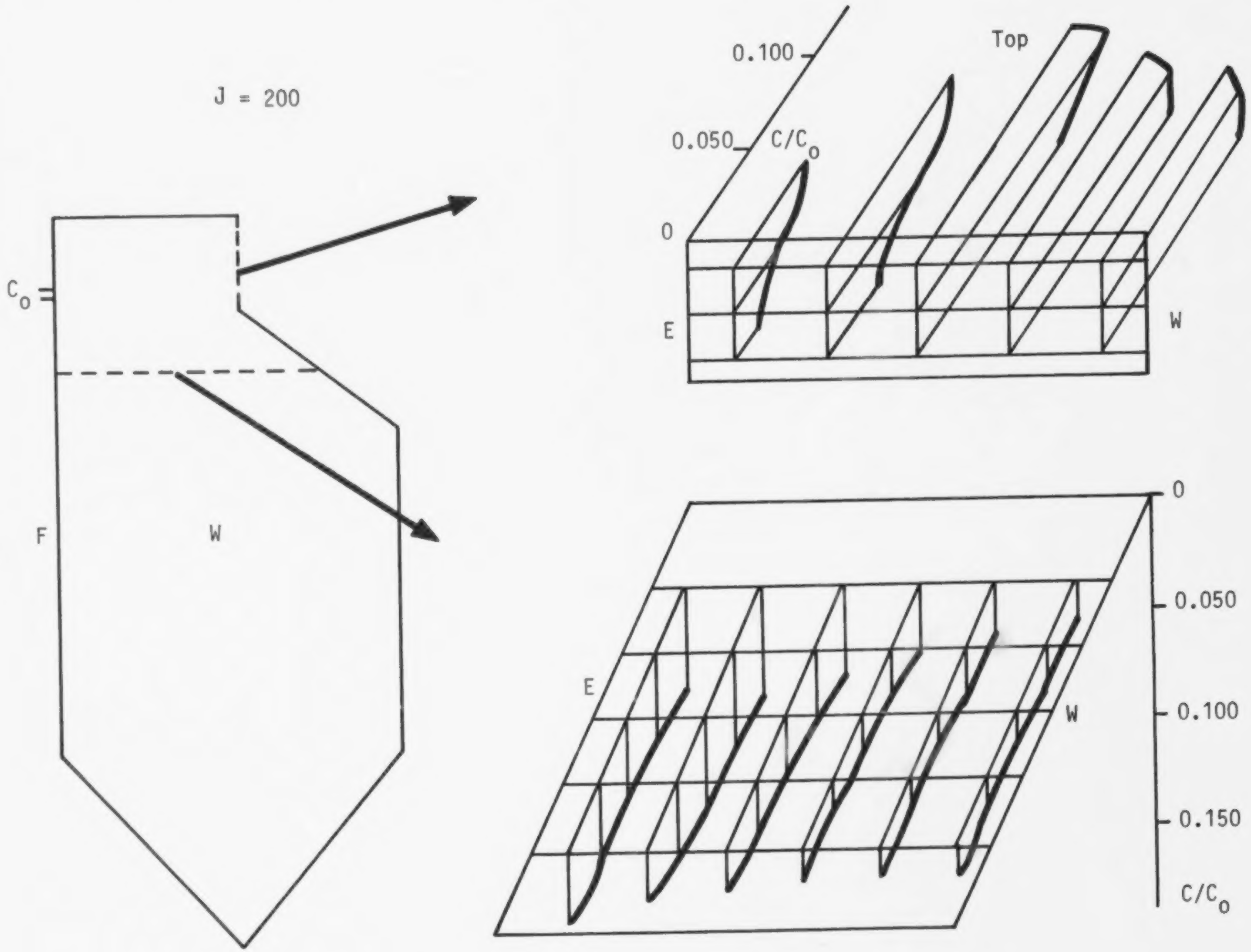


Figure 6-22. Dispersion profiles of tracer in the four jets injected at a momentum flux ratio of 200 at Level IV in the isothermal model of LWS furnace.

devised to determine the relative magnitude of the injection fluid drawn into the lower furnace by the complicated furnace flow in this region. Figure 6-23 refers to the configuration under study. At the upstream measurement location, the local concentration of the jet fluid mixed in the main furnace flow can be approximately written as,

$$C \approx \frac{\dot{m}_t}{\dot{m}_j + \dot{m}_g + \dot{m}_t} \qquad (6\text{-}1)$$

This expression neglects the volume of the recirculated tracer fluid arriving from the main flow which is very small based on the very small fraction of the tracer compared to total furnace flow. Furthermore, making the assumption that $\dot{m}_t << \dot{m}_j$ and $\dot{m}_g$ and noting that

$$\dot{m}_t = C_o \, \dot{m}_j \qquad (6\text{-}2)$$

Equation (6-1) can be simplified and rearranged to give

$$\frac{\dot{m}_j}{\dot{m}_g} = \frac{1}{C_o/C - 1} \qquad (6\text{-}3)$$

This expression gives the approximate fraction of jet to furnace fluid locally in the measurement plane. The total is determined by integrating this quantity across the measurement plane or by summation as

$$\frac{\dot{M}_j}{\dot{M}_{jo}} = \frac{\dot{M}_g}{\dot{M}_{jo}} \sum_{i=1}^{n} \frac{(\dot{m}_g/\dot{M}_g)_i}{C_o/C_i - 1} \qquad (6\text{-}4)$$

Evaluation of this sum requires the knowledge of the flow distribution at the measurement plane. For sake of simplicity, if uniform flow is assumed, then the equation (6-4) can be written as

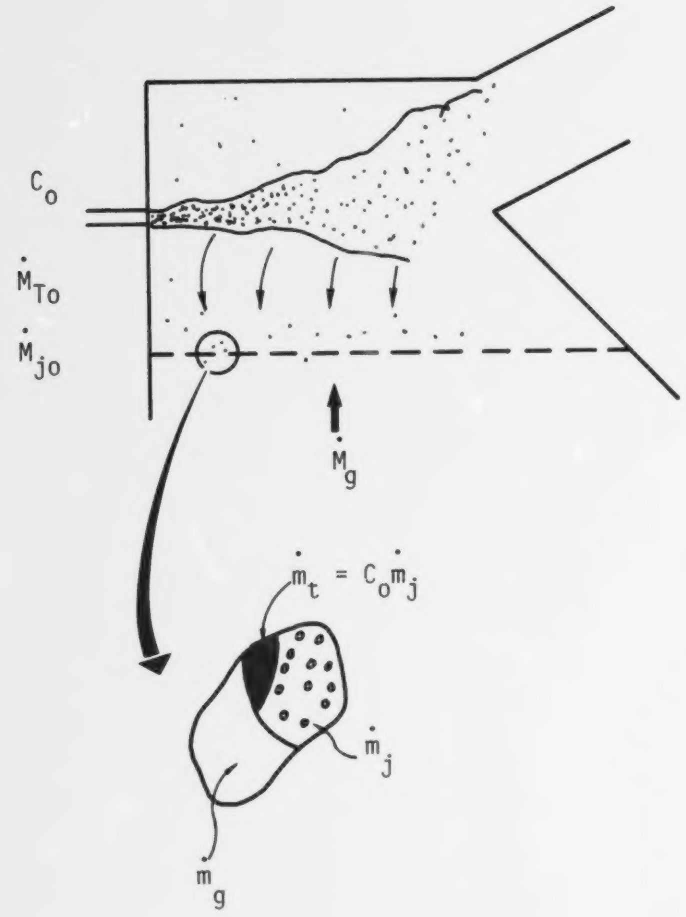

C_o
$\dot{M}_{To}$
$\dot{M}_{jo}$
$\dot{M}_g$
$\dot{m}_t = C_o\dot{m}_j$
$\dot{m}_j$
$\dot{m}_g$

Figure 6-23. Jet fluid dispersion.

$$\frac{\dot{M}_j}{\dot{M}_{jo}} = \frac{\dot{M}_g}{\dot{M}_{jo}} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{C_o/C_i - 1} \tag{6-5}$$

where M_j/M_{jo} is the fraction of the original jet fluid crossing the measurement plane.

The summation can be easily calculated from the tracer measurements. For convenience, if one defines

$$X = \sum_{i=1}^{n} \frac{1}{C_o/C_i - 1} \tag{6-6}$$

then

$$\frac{\dot{M}_j}{\dot{M}_{jo}} = \frac{\dot{M}_g}{\dot{M}_{jo}} \frac{X}{n} \tag{6-7}$$

Letting the fraction of the jet fluid exiting the furnace Z, then,

$$Z = \frac{\dot{M}_{jo} - \dot{M}_j}{\dot{M}_{jo}} = 1 - \frac{\dot{M}_j}{\dot{M}_{jo}} \tag{6-8}$$

or

$$Z = 1 - \frac{\dot{M}_g}{\dot{M}_{jo}} \frac{X}{n} \tag{6-9}$$

This expression allows computation of the fraction of the total jet fluid directly exiting the furnace based on tracer concentration measurements. If it is assumed that the remaining part of the sorbent is deactivated due to exposure to high temperatures and its contribution to the total sulfur capture is negligible, then the overall sulfur capture can be estimated from

$$(\Delta SO_2)_{actual} = Z\ (\Delta SO_2)_{ideal} \tag{6-10}$$

where $(\Delta SO_2)_{ideal}$ is the sulfur capture if all of the sorbent directly exited the furnace. Before determining the actual capture levels, a multiplication constant, γ, was introduced in equation (6-9) in order to account for the non-uniform flow and recirculating tracer in the main flow. With this constant, equation (6-9) can be rewritten as,

$$Z = 1 - \frac{\dot{M}_g}{\dot{M}_{jo}} \ \frac{X}{n} \ \gamma \tag{6-11}$$

γ can be determined by assuming a certain fraction of the total flow exiting the furnace directly. In this exercise, it was assumed that 90 percent of the total jet flow directly exited the furnace while 10 percent was drawn into the lower furnace for the highest jet momentum (J = 221). This yielded a value of $\gamma = 0.198$. Based on the X factors determined from tracer measurements and this value of γ, the Z factors were calculated and multiplied by the predicted sulfur captures to obtain the calculated sulfur captures which includes the effect of sorbent down flow. Table 6-7 shows the results of these calculations for three cases with low, medium and high jet momentum. The predicted and measured sulfur captures were plotted in Figure 6-24 for comparison. It can be seen that good agreement between the predictions and measurements was obtained.

The dependence of sulfur capture on the jet momentum was because of the unique flow field of the LWS furnace and its interaction with the injection jets. This behavior, confirmed with a simple model, is different than the effect of jet momentum in the tower furnace based on the flow field characteristics.

6.2.2 Effect of Jet Diameter

Sorbent injection with smaller diameter jets (4.4 cm) was performed at a jet momentum which gave the same trajectory as the 8.9 cm diameter jets at a

TABLE 6-7. SUMMARY OF PREDICTED AND MEASURED SULFUR CAPTURES SHOWING EFFECT OF J

Jet to Cross Flow Momentum Ratio, J	$\dot{M}_g/\dot{M}_{jo}$	X	n	Z	$(\Delta SO_2)_{ideal}$ @ Ca/S=3.0	$(\Delta SO_2)_{pred.}$ @ Ca/S=3.0	$(\Delta SO_2)_{meas.}$ % Ca/S = 3.0
53	30.9	1.830	30	0.627	69.7	43.7	49.0
157	20.9	0.924	30	0.862	76.5	65.9	61.0
221	18.8	0.807	30	0.900(*)	74.8	67.3	77.0

(*) This value was chosen arbitrarily as discussed in the text. The value of γ corresponding to the X and Z values for this case was computed from equation (6-11) to be 0.198.

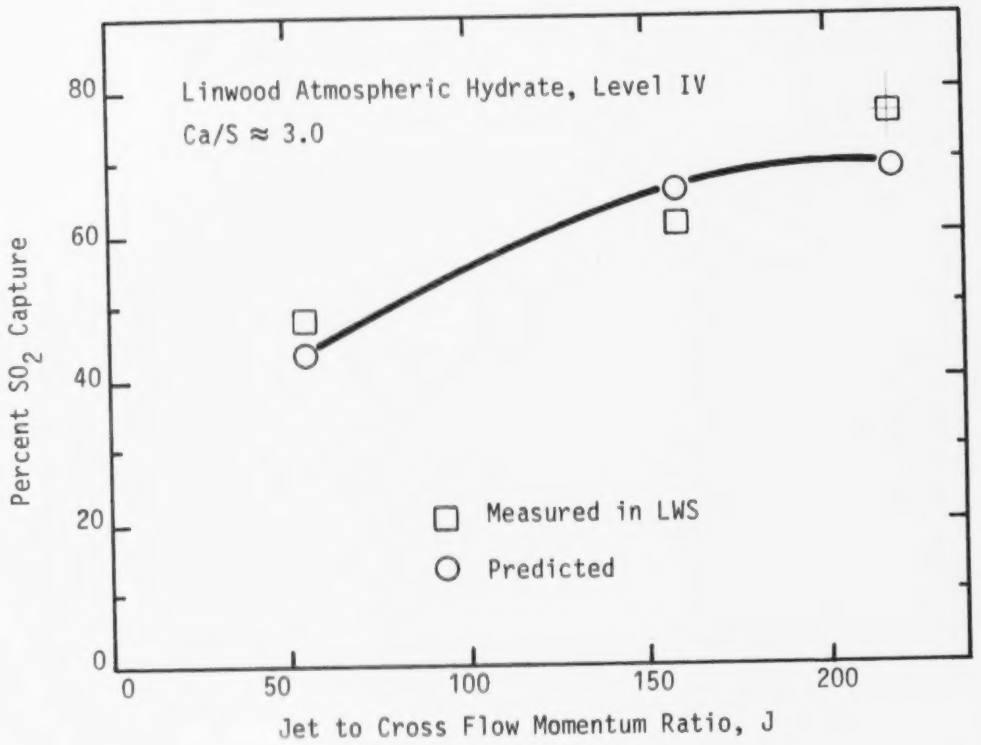


Figure 6-24. Comparison of measured and predicted sulfur capture in the LWS furnace (Level IV injection).

momentum flux ratio of 150. The required jet momentum ratio was determined from equation (3-2). The results are shown in Figure 6-25. The capture levels with 8.9 cm and 4.4 cm diameter jets were similar. Total entrainment of the flue gas into the sorbent jets was calculated for both cases to explain this behavior. It was found that the difference in the initial jet mass flows due to different jet velocities was compensated by the effect of jet diameter on the total entrainment, both systems having the same entrainment with physical distance along the jets. Hence, both 4.4 cm and 8.9 cm jets had similar sulfur captures. Doubling the jet momentum from J = 500 to J = 1000 resulted in increase of the sulfur capture similar to the 8.9 cm jets shown in Figure 6-15.

6.2.3 Effect of Number of Jets

Several jet configurations at injection Level IV were tested to determine the effect of dispersion on the sulfur capture. These included all four jets, two jets on one side and two middle jets. The results are shown in Figure 6-26. There was no significant effect on sulfur capture. This is possibly due to the rapid mixing of the sorbent stream with the high velocity flue gas jet stream near the back wall and the small influence of dispersion in the low velocity recirculating flow field. This effect is again due to the particular flow field of the LWS furnace and has to be considered within its context only.

6.2.4 Effect of Injection Temperature (Elevation)

Tests at two levels with Linwood atmospheric hydrate were done to investigate the effect of injection temperature on sulfur capture. The test results, shown in Figure 6-27, indicate that sulfur capture during high temperature injection was lower. This result is in accordance with the bench and pilot scale sorbent injection tests where an optimum injection temperature around 1200°C was identified.

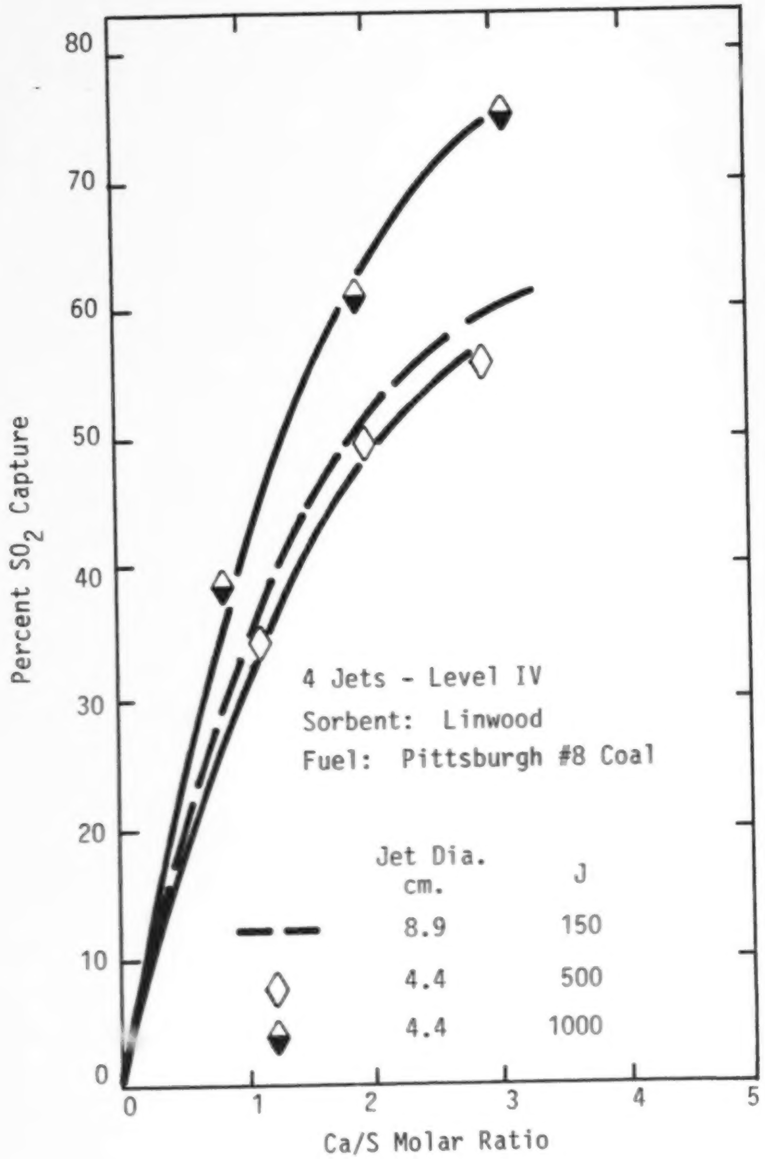


Figure 6-25. Effect of jet diameter and momentum on sulfur capture with Linwood atmospheric hydrate at Level IV.

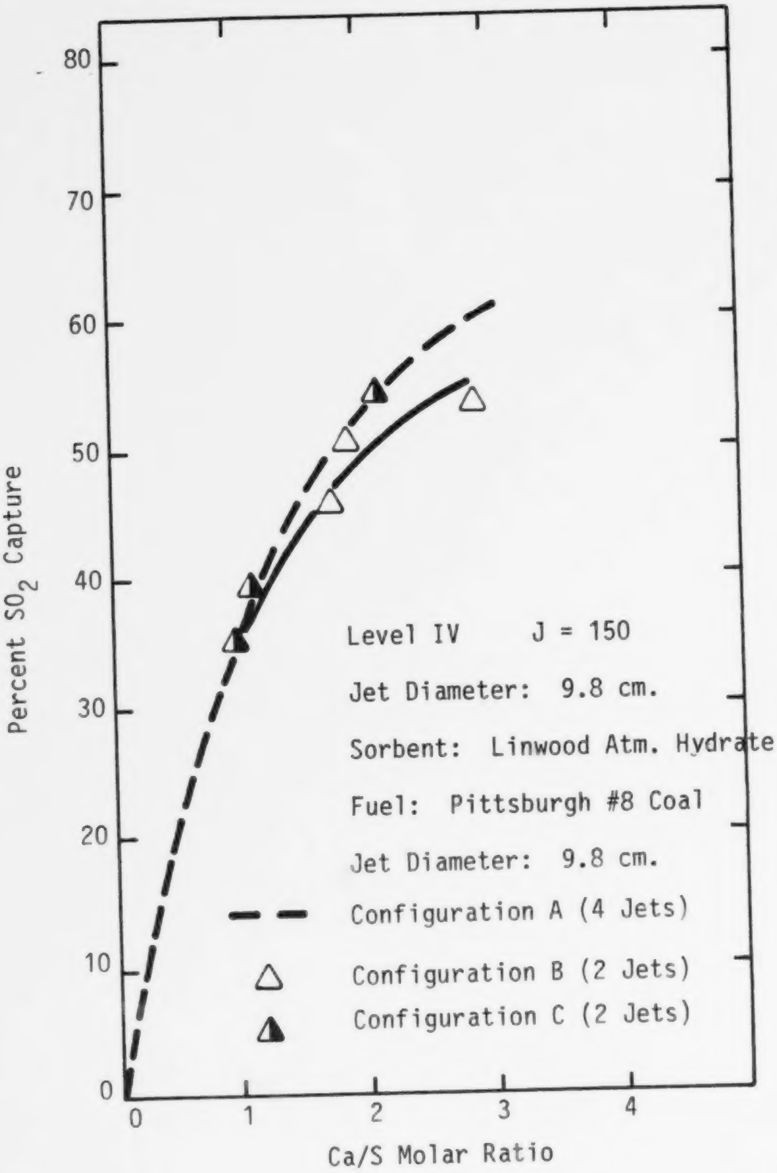


Figure 6-26. Effect of number of jets on sulfur capture with Linwood atmospheric hydrate at Level IV.

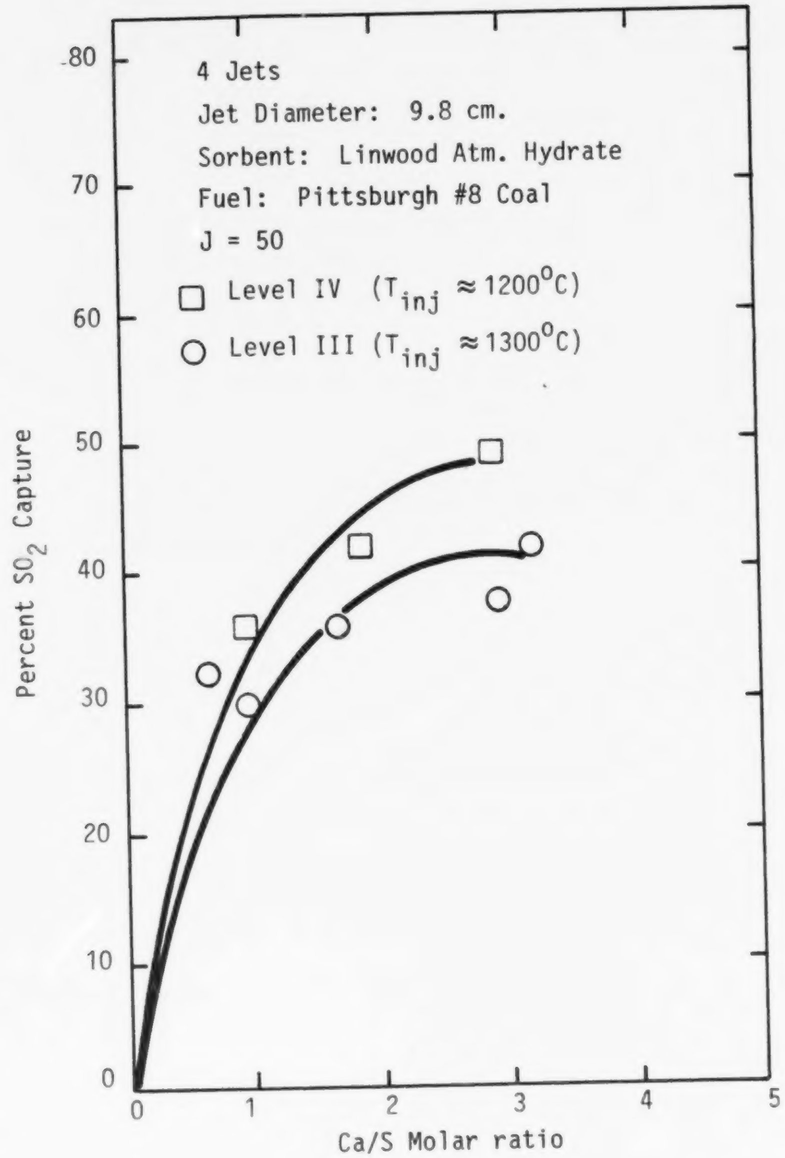


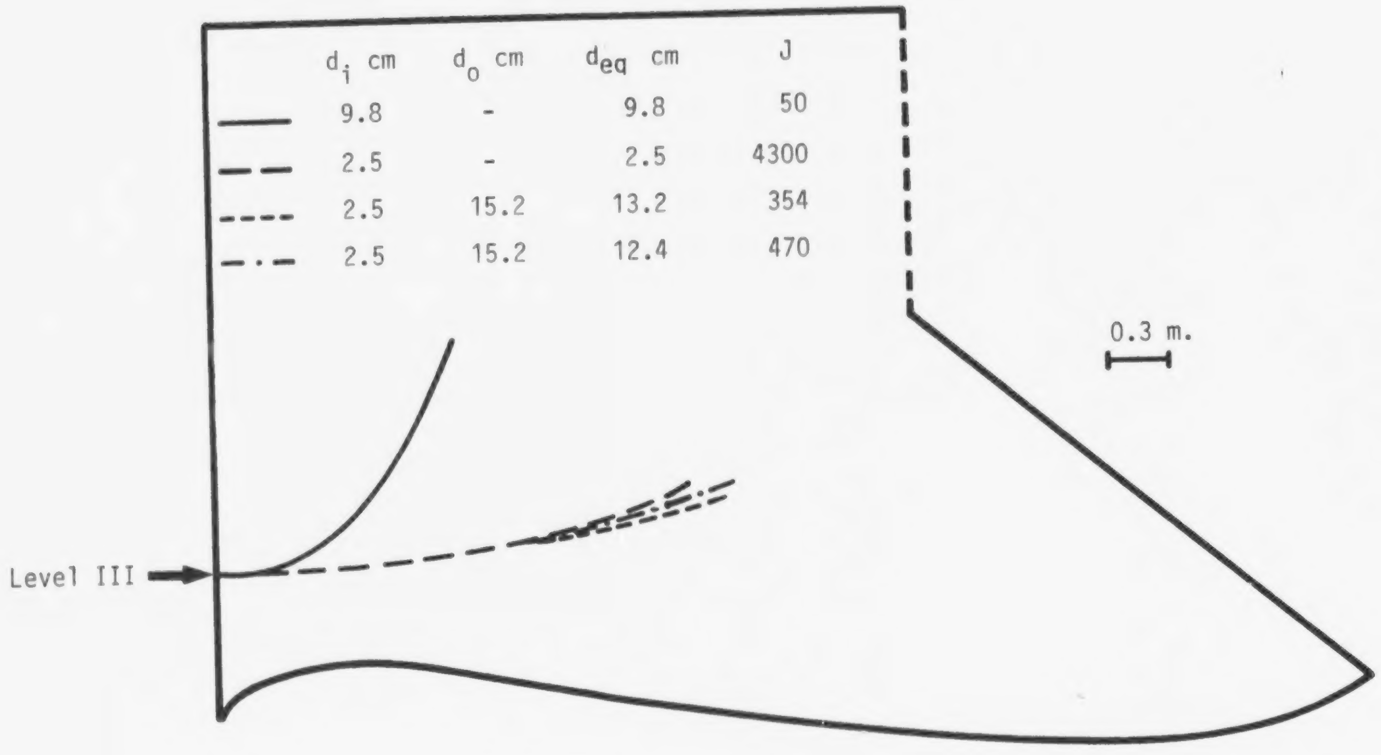
Figure 6-27. Effect of injection location on sulfur capture with Linwood atmospheric hydrate.

6.2.5 Double Concentric Jets

In the previous sorbent injection tests, it was found that there was some benefit of shielding the sorbent jets with a secondary annular jet stream. This was believed to be due to either thermal shielding of the sorbent jets in the initial mixing zone or the enhanced penetration characteristics of these jets. During these tests, some tests with double concentric jets were performed. Three tests were conducted at Level III with Linwood atmospheric hydrate.

- 2.5 cm diameter, single jets, J = 4300
- 2.5 cm inner diameter, 15.2 cm outer diameter, double concentric jets, J = 350
- 2.5 cm inner diameter, 15.2 cm outer diameter, double concentric jets, J = 470

Figure 6-28 shows the fictitious jet trajectories calculated from equation (3-2) based on the uniform average cross flow conditions. Although it is known that the jets at this location experience a down flow, the relative penetration behavior of the different diameter and velocity jets can be interpreted based on these trajectory predictions. It is apparent that 2.5 cm diameter simple and double concentric jets all had similar jet trajectories while the 9.8 cm diameter simple jets with J = 50 were much more prone to bending by the cross flow. Figure 6-29 shows the sulfur capture under these three injection conditions and compares them with the lowest momentum (J = 50) 9.8 cm diameter jets. The 2.5 cm diameter simple and the two double concentric jets gave similar sulfur capture as it would be expected based on their trajectories. The 9.8 cm low momentum jets showed lower capture since they were bent in the furnace flow significantly more than the other cases. This was reflected by the lower captures with the 9.8 cm-low momentum jets.



	d_i cm	d_o cm	d_{eq} cm	J
———	9.8	-	9.8	50
— —	2.5	-	2.5	4300
- - - -	2.5	15.2	13.2	354
—·—	2.5	15.2	12.4	470

Figure 6-28. Fictitious sorbent jet trajectories based on assumed nose plane cross flow conditions.

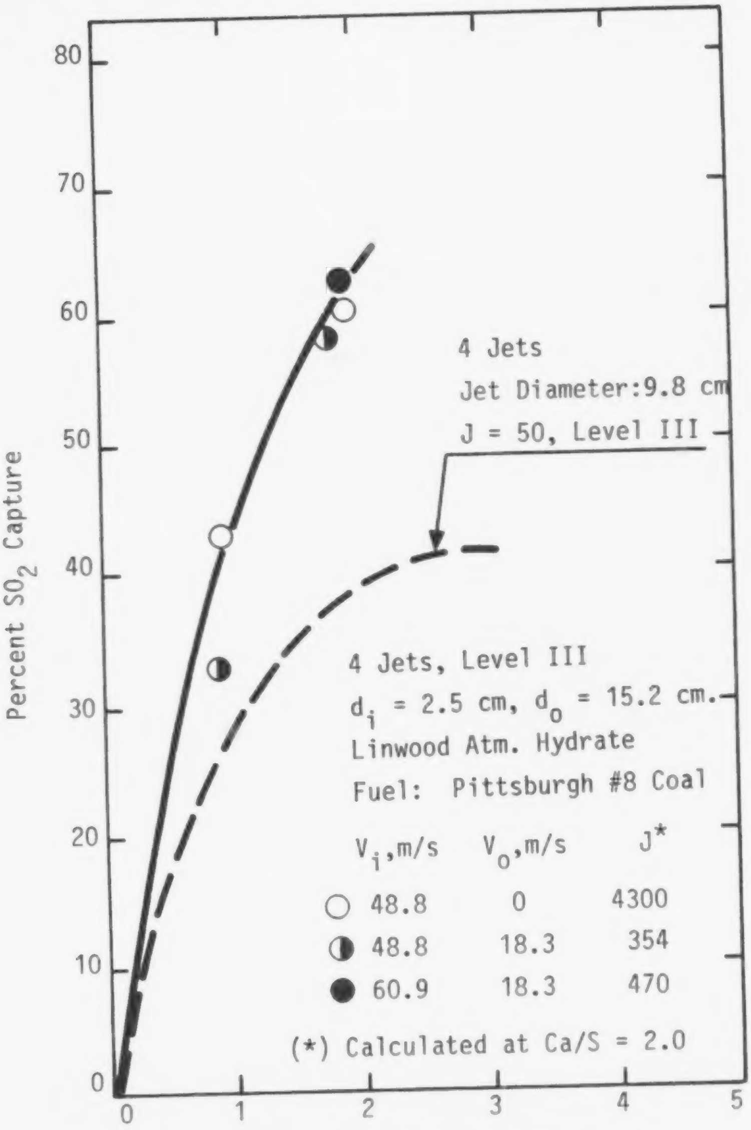


Figure 6-29. Sulfur capture with single and double concentric jets at Level III with Linwood atmospheric hydrate.

6.2.6 Sorbent Type

Limited number of tests were conducted with Vicron 45-3 ($CaCO_3$) and Colton lime ($Ca(OH)_2$) to compare their performance with Linwood atmospheric hydrate. Figure 6-30 shows the measured sulfur captures and the comparisons. Capture levels with Vicron 45-3 were similar to the earlier upper furnace injection tests reported earlier (24). The capture levels with Vicron 45-3 and Colton lime were similar, but both gave lower captures than Linwood atmospheric hydrate under similar injection conditions. Higher captures with Linwood could be possibly attributed to the finer size of this sorbent as shown in Figure 6-10. There was not a significant effect of jet momentum as this parameter was varied in a small range. A change in momentum flux by 33 percent translated to a change in velocity by approximately 15 percent.

6.3 Summary of Sorbent Injection Tests in the LWS Furnace

The sorbent injection tests performed in the LWS upper furnace showed some behavior which was contrary to the results obtained during pilot scale tests in the tower furnace.

- Upper level sorbent injection showed a significant dependence of sulfur capture on the jet momentum while this was found to be a small effect during pilot scale tests.

- Effect of dispersion was small in the LWS injection tests while it was found that this effect was important as the dispersion of sorbent into the furnace flow was degraded.

However, these contradicting results are believed to arise from the nature of the flow field in the LWS furnace and its interaction with the sorbent injection jets. Isothermal modeling in a 1/15 scale acrylic model of LWS furnace and the LWS furnace itself indicated that some of the sorbent was drawn down into the lower furnace, thus experiencing high temperatures and deactivation. A simple model in conjunction with the isothermal tests

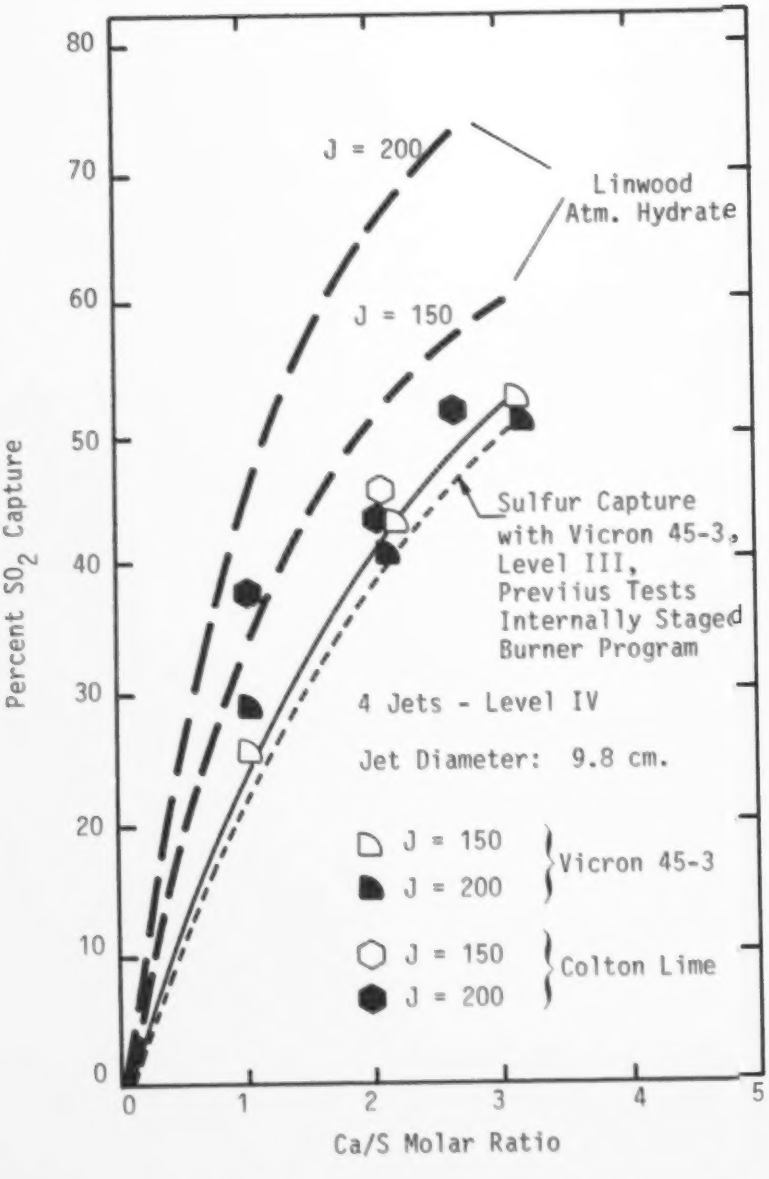


Figure 6-30. Sulfur capture dependence on sorbent type.

provided an explanation of the sulfur capture dependence on the jet momentum for these particular LWS tests.

Test results from injection with different diameter and momentum jets as well as double concentric jets could be explained with the entrainment characteristics and trajectories of these sorbent jets.

Test results showed that sulfur captures of about 70 percent at Ca/S molar ratio of 2.0 are possible in the LWS furnace. However, care should be taken in interpreting these results in an attempt to predict sulfur capture potential at a utility boiler with different flow characteristics, geometry and thermal environment.

7.0 SORBENT INJECTION SYSTEM DESIGN METHODOLOGY

The main goal of this project was to develop a methodology comprised of a set of empirical, experimental and computational procedures to design sorbent injection systems for wall-fired utility boilers. The basic approach was building up a methodology based on the understanding of the jet injection and mixing processes. For this purpose, the isothermal modeling studies, described in Section 3.0 of this report, were conducted to investigate the jet mixing processes in boiler-furnace configurations without the complexity of the combustion process and the non-isothermal effects. Key parameters of jet injection process and methods of modeling a non-isothermal mixing process isothermally were investigated. The findings from the isothermal modeling studies were used to aid in the development of computational models of jet injection process as discussed in Section 4.0. Since the ultimate goal of the project was to provide a design methodology for injection systems which will give optimum sulfur capture efficiency, the influence of the key injection parameters, identified in Sections 3.0 and 4.0, were tested in two combustion experiments to determine their overall influence on sulfur capture.

Pilot scale injection studies were conducted in a combustion chamber closely simulating a boiler upper furnace at a heat release rate of 1.23 MW_{th} (4.5×10^6 Btu/hr). The results of these studies were described in Section 5.0. Two schemes, one based on isothermal modeling and the other based on computational models, were devised to explain the results. These predictive schemes are part of the methodology described below. Combustion tests were also conducted at a larger scale, 24 MW_{th} (80×10^6 Btu/hr) heat input, to further investigate the scale effects. The test results were presented in Section 6.0.

This section of the report is aimed to document a sorbent injection system design methodology based on the knowledge developed in the preceding sections. The outcome is a hierarchy of design and interpretation procedures which can be used in the design and data interpretation phases. The three levels of sophistication for the methodology consists of:

(I) Use of simple empirical relationships which were developed and tested in this study. These refined formulas can be used to determine the injection system parameters (number, size, and velocity of injection jets) based on the operational characteristics of the boiler and other constraints such as the availability of injector sites.

(II) Isothermal modeling can be used together with Level (I) results to study the effects of varying the injection system parameters roughly determined in (I) and optimize mixing in an isothermal model. This requires construction of an isothermal model of the boiler furnace (or at least the upper furnace) and study of dispersion of the sorbent jets in the furnace flow. This scheme also provides an empirical predictive capability which can be utilized to predict the sulfur capture potential for particular injection systems.

(III) Computational models of jet injection and calcination/sulfation processes to investigate and predict the time-dependent nature of the sorbent injection process.

In the following subsections, each element of the methodology will be discussed. Examples of the methodology application will be given in Section 8.0.

7.1 Empirical Procedures

An injection system design has to satisfy three requirements. These are:

- Sorbent jets are required to penetrate into the cross flow of the furnace gases in order to achieve distribution of the sorbent within the furnace flow.

- Along with the penetration of the jets, the sorbent jets have to engulf as much of the furnace flow as possible in a small space and short time near the injection location.

- The above two requirements need to be satisfied within the injection carrier flow rate and pressure drop requirements.

The task is then to determine the optimum set of three jet system parameters to satisfy the three requirements stated above. The injection system parameters are:

- jet size (diameter)
- injection velocity
- number of jets

Isothermal studies in Section 3.0 resulted in a refined jet trajectory correlation for a jet injected into a uniform cross flow. This correlation had the following form,

$$\frac{y}{d_o} = J^{0.43} \left(\frac{x}{d_o}\right)^{0.36} \tag{7-1}$$

where the jet coordinate system and the jet parameters are described in Figure 7-1. This correlation was tested in boiler flow fields near the nose region and found to give a reasonably accurate estimate of the early part of the jet trajectory. Therefore, equation (7-1) can be used to assess the jet penetration for the first requirement.

The second requirement is a more difficult one to express analytically because of the lack of entrainment data and entrainment correlations for a jet injected into a cross flow. However, it is known that a jet in cross flow entrains significantly faster than a free jet due to the presence of the cross flow field. In order to provide a rough estimate of jet entrainment,

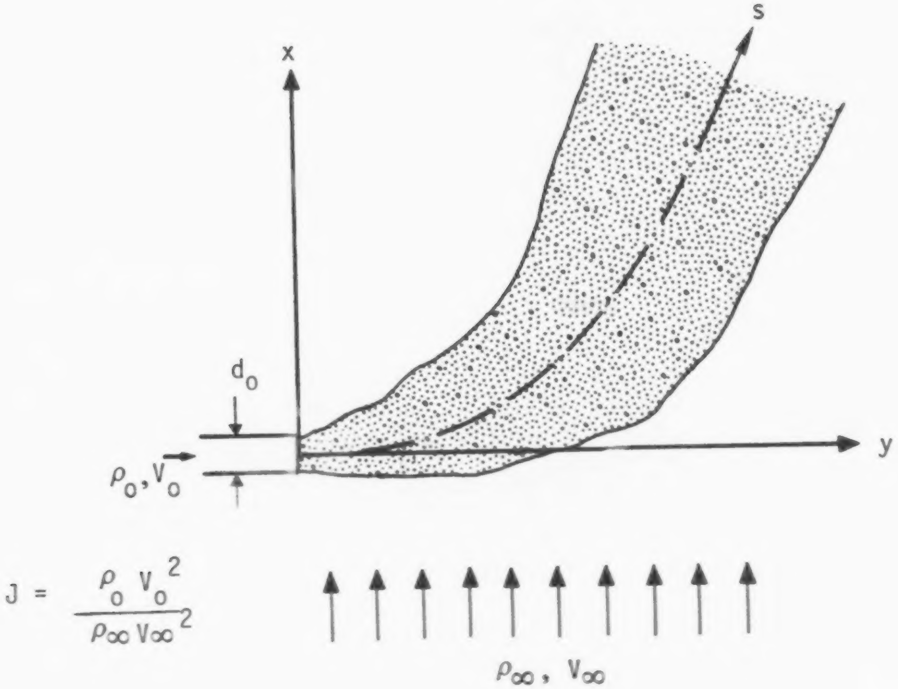

x
s
y
d_o
$\rho_o, \vec{V_o}$
$J = \frac{\rho_o V_o^2}{\rho_\infty V_\infty^2}$
ρ_∞, V_∞

Figure 7-1. Orientation of a jet in cross flow.

the free jet entrainment can be modified by an empirical factor. The correlation suggested here is,

$$\frac{\dot{M}}{\dot{M}_o} = 0.32 \left(\frac{\rho_\infty}{\rho_o}\right)^{1/2} \left(\frac{s}{d_o}\right) \phi(J) \tag{7-2}$$

where M is the total mass flow in the jet, M_o is the mass flow in the jet at the origin, s is the distance along the jet, d_o is the jet diameter, ρ_∞ and ρ_o are the ambient fluid and the jet fluid densities respectively. Finally, ϕ is an empirical factor which is equal to 1.0 for the free jet and varies according to Figure 7-2 with the jet to cross flow momentum flux ratio. The dependence of ϕ on the momentum flux ratio was obtained from the computational model of a jet in cross flow discussed in Section 4.0. In applying this equation, caution should be taken in terms of the limiting ranges of the parameters for which the correlation was developed.

The third requirement is a practical constraint which is related to the maximum amount of carrier fluid which is needed for sorbent injection. This can be expressed mathematically as,

$$\dot{M}_T = n \frac{\pi d_o^2}{4} V_o \rho_a \tag{7-3}$$

where n is the number of jets, d_o is the jet diameter, V_o is the jet velocity and ρ_a is the injection fluid density.

At this stage, it can be stated that there are three unknowns which are the number, size and velocity of injection jets and they can be determined from the three equations expressed by equations (7-1), (7-2) and (7-3) uniquely. However, this is easier said than done because of the nature of the empirical equations. Rather than devising a complicated solution procedure, a simpler iterative approach was preferred. A flow chart for determination of the jet parameters is given in Figure 7-3. The boiler operating and input conditions are the first pre-requisites in determining

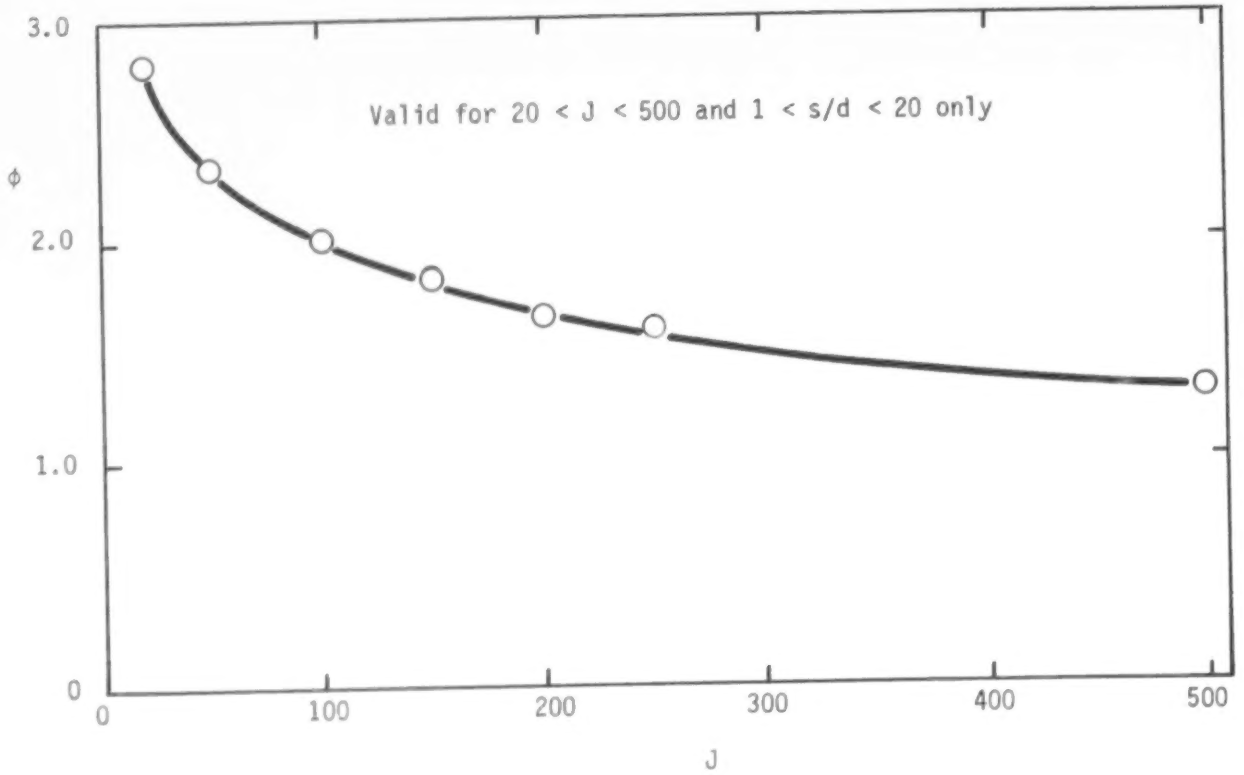


Figure 7-2. Variation of entrainment coefficient, ϕ, with the jet to cross flow momentum flux ratio.

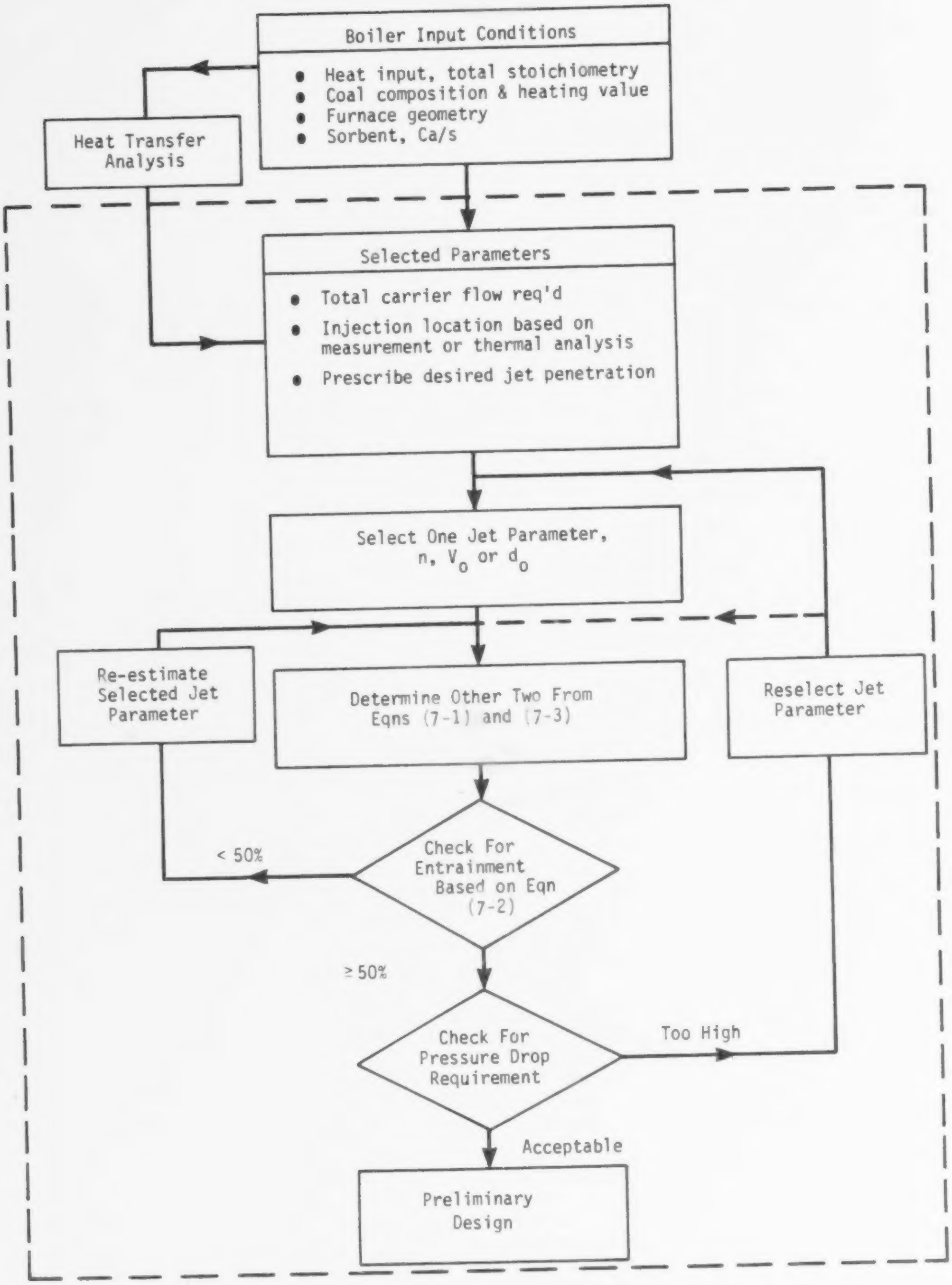

Boiler Input Conditions
• Heat input, total stoichiometry
• Coal composition & heating value
• Furnace geometry
• Sorbent, Ca/s
Heat Transfer Analysis
Selected Parameters
• Total carrier flow req'd
• Injection location based on measurement or thermal analysis
• Prescribe desired jet penetration
Select One Jet Parameter, n, V0 or d0
Re-estimate Selected Jet Parameter
Determine Other Two From Eqns (7-1) and (7-3)
Reselect Jet Parameter
< 50%
Check For Entrainment Based on Eqn (7-2)
≥ 50%
Check For Pressure Drop Requirement
Too High
Acceptable
Preliminary Design

Figure 7-3. Preliminary sorbent injection system design methodology.

the injection parameters. As a minimum, the following information on boiler design and operation is required to start the sorbent injection system design:

- Furnace engineering drawings

- Operational data including

    - Furnace heat input and overall stoichiometry
    - Fuel characteristics (composition and heating value)
    - Any available data on gas and steam side temperatures in the upper furnace

First of all, the approximate location of the sorbent injectors need to be specified. Typically, this should be based on the thermal environment in the upper furnace determined by either gas temperature measurements or a detailed heat transfer modeling of the furnace under investigation. Based on the measured and/or predicted temperature levels, the injection location for the upper furnace is placed in a region where gas temperatures typically lie between 1200°C (2192°F) and 1260°C (2300°F).

Additional specifications include the maximum allowable sorbent carrier flow and the desired trajectory of the jets based on the furnace dimensions at the injection plane. As an example, in a 20 m wide furnace where injectors can be placed on opposite sides, the trajectory specification can be given for the jets to penetrate 10 m with a 2 meter rise at this penetration. This prescription is somewhat arbitrary, but it is defined in order to eliminate cases with unreasonable trajectories. The next step involves prescription of one of the jet parameters among the three (number of jets, jet velocity and jet diameter) to determine the other two parameters from the other constraints. The determined jet parameters are put to test for entrainment to determine the degree of entrainment of the furnace flow. For example, a few large diameter jets at low velocity and many small diameter jets at high velocity can satisfy the trajectory and flowrate constraints. However, their entrainment characteristics will be significantly different since small jets entrain much more ambient fluid than the large jets for the same total jet flow. If the entrainment test is passed, then pressure drop requirements would be checked optionally to determine if the blower requirements are within the system capabilities. If all conditions and requirements are satisfied, this dictates a preliminary sorbent injection system design.

In order to refine this preliminary sorbent injection system design, isothermal modeling of injection systems can be performed in a subscale acrylic model.

7.2 Isothermal Modeling

Isothermal modeling of sorbent injection schemes is a useful tool in analyzing and optimizing the performance of a preliminary injection system design obtained from empirical procedures. For this purpose, either a subscale model of the full furnace including burners or a model of the upper furnace including the nose section can be constructed. The main criteria in the design of an isothermal model are:

- geometric similarity
- dynamic similarity of the flow field based on the bulk Reynolds number of the flow

A typical size of a full furnace model for isothermal studies can be in the range of 1.8 m (6.0 ft) to 2.4 m (8.0 ft) in height. This makes the testing and construction of the model easier than larger size models. In general, the exact Reynolds number similarity cannot be achieved in air models operating at moderate velocities. However, it is adequate to achieve a Reynolds number greater than 15,000 (based on the hydraulic diameter of the furnace cross section) for dynamic flow field similarity.

Isothermal testing of injection systems can be comprised of several different tests. These are:

- Main flow field characterization by flow visualization and velocity measurements near injection region
- Smoke jet screening studies for qualitative observations of dispersion of injection jet stream into the main flow field
- Tracer concentration measurements to quantify the degree of mixing of the injection jets in the main flow field

These tests allow refinements of the preliminary injection schemes since the main flow field is more realistically simulated in an isothermal model. In addition to the value of isothermal modeling in optimization of injection system designs, the results can also be used to estimate the potential sulfur capture levels with an empirical methodology. This methodology, described and tested in Section 5.0, can be easily explained with the help of Figure 7-4. In this approach, the measured steady-state tracer concentration profiles are utilized to determine the local Ca/S molar ratio distribution across a plane downstream of sorbent injection plane. This is done simply by multiplying the overall well-mixed Ca/S molar ratio with the normalized tracer concentrations (local concentration divided by the well-mixed exhaust value). The local Ca/S molar ratios can then be used in conjunction with a sulfur capture versus Ca/S molar ratio curve obtained under similar experimental conditions in a combustor where effect of mixing is small. These data allow determination of the individual sulfur capture contributions of the various furnace streams based on the local Ca/S stoichiometries. The final step in the procedure is to superimpose the effect of the flow field, i.e. distribution of the furnace gas flow, on the overall sulfur capture. This is achieved by carrying out the sum,

$$\Delta SO_{2,\text{overall}} = \sum_i \frac{\dot{M}_i}{\dot{M}_T} (\Delta SO_2)_i \qquad (7\text{-}4)$$

where $\dot{M}_i/\dot{M}_T$ represents the flow distribution and summation is carried out across the cross section. The calculated overall sulfur capture value is an

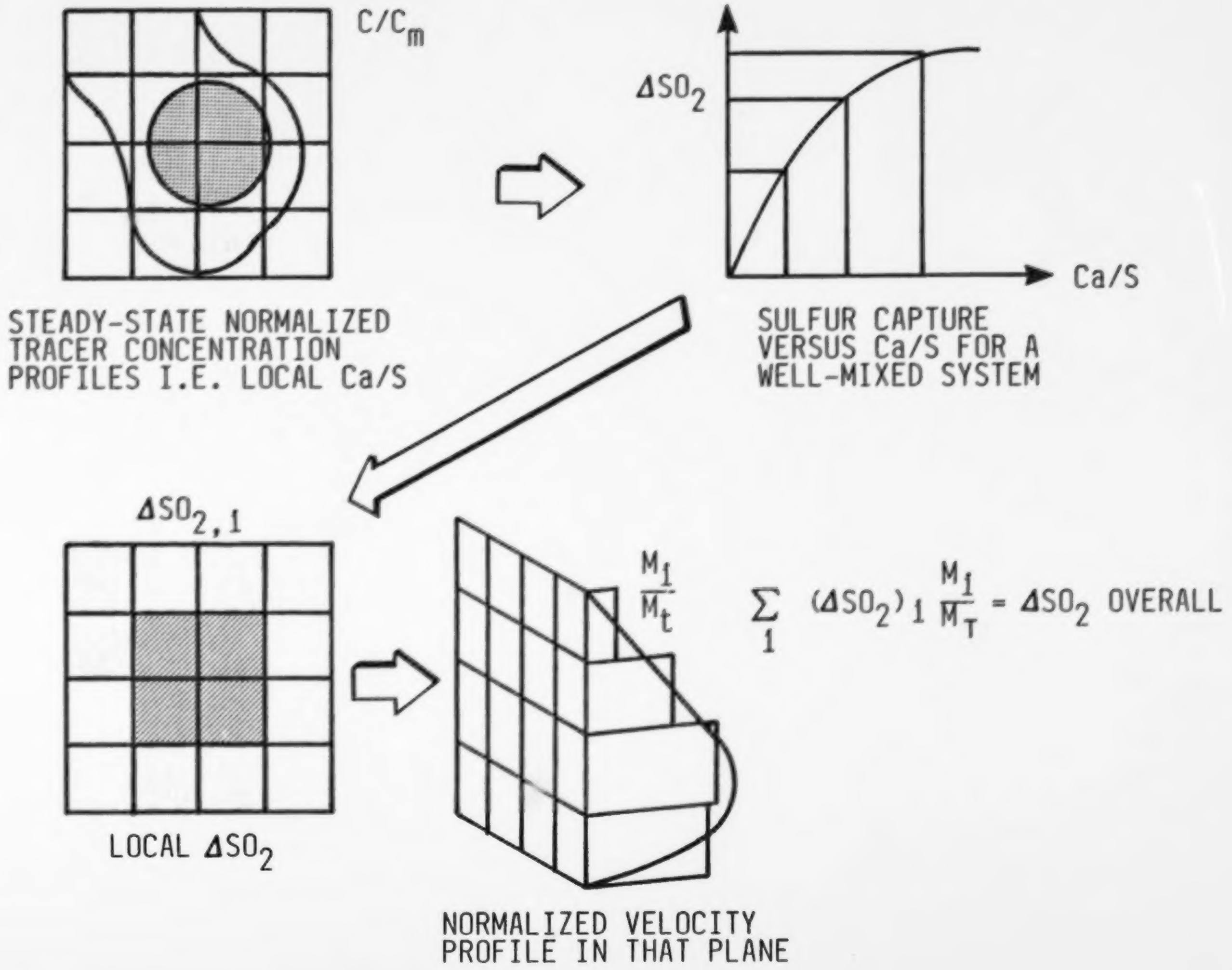

C/C_m
STEADY-STATE NORMALIZED TRACER CONCENTRATION PROFILES I.E. LOCAL Ca/S
ΔSO_2
Ca/S
SULFUR CAPTURE VERSUS Ca/S FOR A WELL-MIXED SYSTEM
$\Delta SO_{2,i}$
LOCAL ΔSO_2
$\frac{M_i}{M_t}$
NORMALIZED VELOCITY PROFILE IN THAT PLANE
$\sum_i (\Delta SO_2)_i \frac{M_i}{M_T} = \Delta SO_2$ OVERALL

Figure 7-4. Empirical methodology to predict effect of dispersion on sulfur capture.

estimate of the sulfur capture in the boiler at the same overall well-mixed Ca/S ratio.

The next level of sophistication involves use of computational models of jet mixing and calcination/sulfation models as discussed in the next subsection.

7.3 Computational Approach

The computational model of jet injection into a cross flow can be used both as a design tool or as a part of a predictive methodology for sulfur capture estimations. The jet model, described in Section 4.0, can be used to replace some of the empirical steps in the empirical methodology discussed in Subsection 7.1. The empirical trajectory equation and the entrainment correlation can be replaced by the jet model which computes these as a part of the solution. Furthermore, the jet model modified for furnace type non-uniform flow fields can be employed in injection system design. This would allow a more realistic estimation of the jet behavior than empirical correlations based on uniform cross flow experiments.

The jet model also provides the initial conditions for the calcination/sulfation models. The temperature-time and Ca/S molar ratio-time profiles computed by the jet model can be used in the sulfur capture model to predict the progress of sulfation as shown in Figure 7-5. However, this predictive scheme is still in its preliminary stages especially due to the existing uncertainties and knowledge gaps of the calcination/sulfation process. The predictions from this scheme should therefore be interpreted with caution.

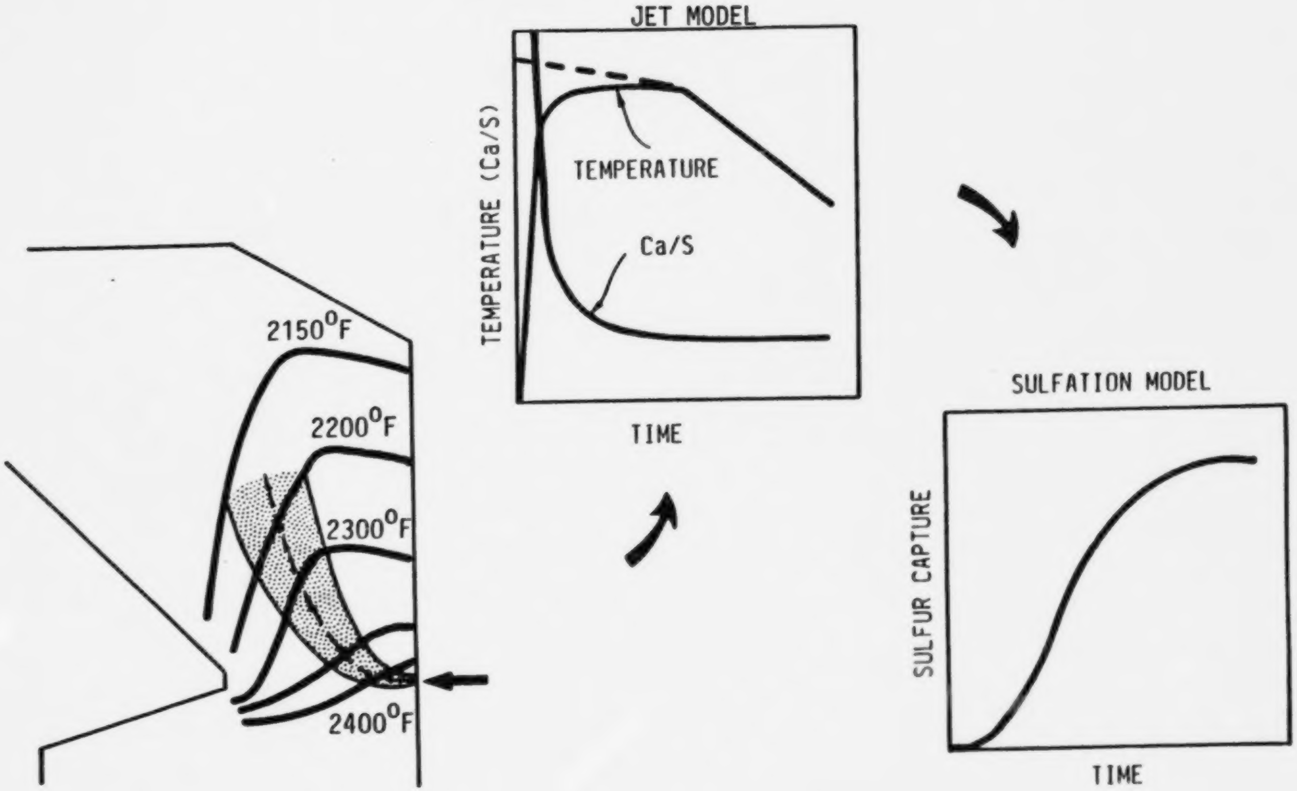

JET MODEL
TEMPERATURE (Ca/S)
TEMPERATURE
Ca/S
TIME
SULFATION MODEL
SULFUR CAPTURE
TIME
2150°F
2200°F
2300°F
2400°F

Figure 7-5. Predictive scheme to determine the progress of sulfation in sorbent injection jets.

8.0 METHODOLOGY APPLICATION TO A UTILITY BOILER

In this section, the elements of methodology described in Section 7.0 were used to make preliminary predictions of expected sulfur removal efficiency at the EPA's LIMB demonstration boiler (Edgewater) with two atmospherically hydrated limes (Linwood and Marblehead). The predictions were based on isothermal modeling of Edgewater boiler furnace (conducted for EPA under subcontract from Babcock and Wilcox) and computational jet mixing and calcinaltion/sulfation models. The five elements used in making the sulfur capture predictions were:

(1) Thermal Analysis Code (GBTAC) to provide the spatial gas temperature distributions and temperature histories through the upper furnace regions where sorbent injection was considered. This is one of the key elements so far as the injection locations and sulfation process is concerned.

(2) Isothermal Physical Modeling of boiler flow patterns and jet injection schemes. The boiler flow patterns obtained from isothermal modeling was input to the thermal analysis code. In addition, isothermal modeling provided a valuable means to assess the performance of various sorbent jet injection schemes in terms of mixing and dispersion.

(3) Modeling of jets in cross flow (JICFIS) enabled prediction of entrainment, temperature history of the gas and particles in a jet in addition to the location of the jet (trajectory and spread). This model could handle jets in uniform flow and non-uniform boiler flows and was verified by experimental data. This model was used in conjunction with EER's sulfation model to estimate the effect of initial jet transients on sulfur capture for the relevant injection configurations.

(4) Sulfation model was used to calculate sulfation of calcium oxide particles in an SO_2 containing gas. This model takes account of

the resistances to diffusion of SO_2 through the particle boundary layer, along the particle pores and across the product layer before reacting at the surface of the oxide particles. It also takes account of the sintering and loss of surface area that occurs when CaO particles are held at high temperature. The overall utilization of calcium is then found from holding the calcium in a prescribed environment which is varying in temperature and SO_2 concentration as a result of mixing with the free stream and removal of SO_2 by the sulfation process. The model has been calibrated against data measured in the Controlled Temperature Tunnel (CTT), but shows a much greater dependence of Ca utilization on partial pressure of SO_2 than has been observed in these experiments, although it matches well with other small scale experimental data (e.g. Borgwardt 1984). There are some unanswered questions about the validity of this model but it represents one way that experiments on one system can be scaled for predicting captures in another system. This model was used in conjunction with the jet model to determine the effects of jet injection and quench rates.

(5) Pilot scale combustion experiments were conducted with an upper furnace configuration similar to Edgewater boiler. These tests, described in Section 5.0, involved sorbent injection in the upper furnace with several injection configurations under boiler simulated flow and thermal conditions. The relevant test data were also used in predicting sulfur capture with Linwood atmospheric hydrate.

In the following, first the thermal environment predictions for the Edgewater boiler are discussed. The results from isothermal modeling of sorbent injection configurations are presented and analyzed for carrier air injection flow rates at full scale. Finally, some sulfur capture predictions are presented for the Edgewater boiler.

8.1 Thermal Environment

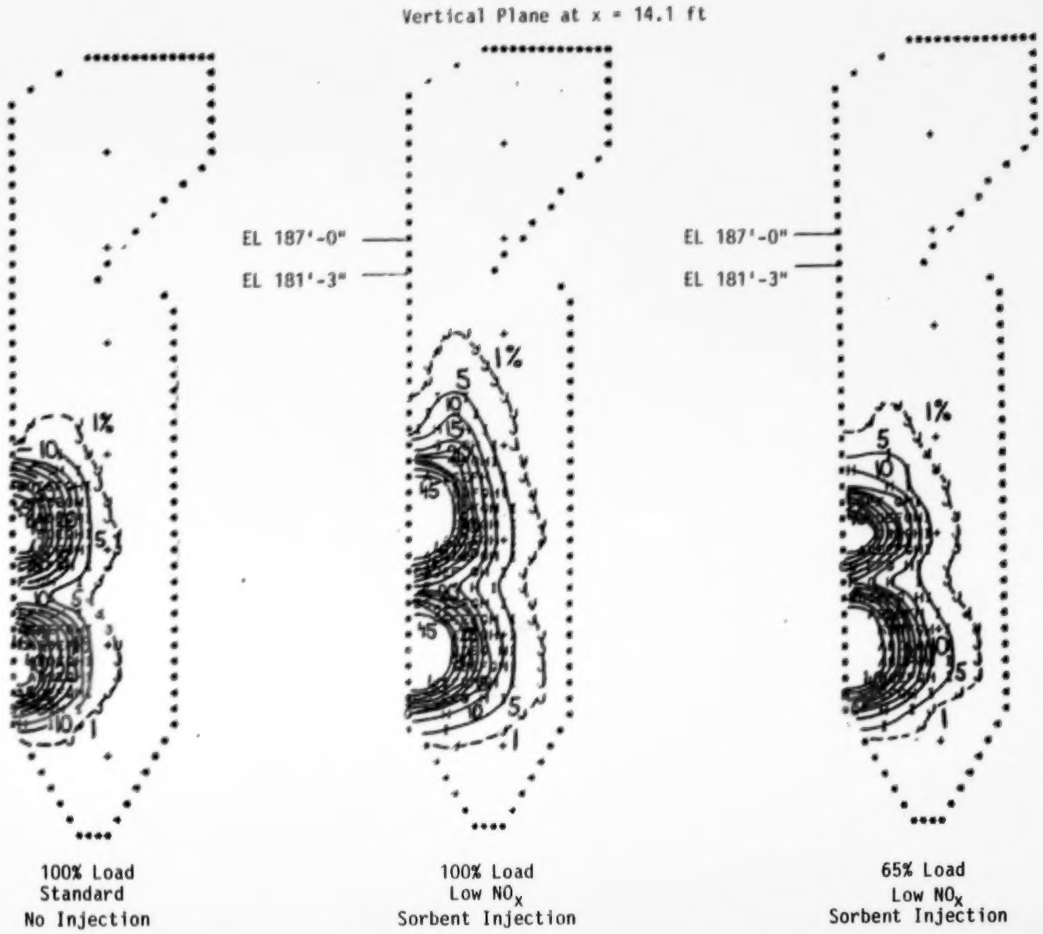
Predictions of boiler thermal environment were made with GBTAC three-dimensional boiler thermal analysis code. Calculations utilized the flow patterns obtained from isothermal modeling and the results were compared with temperature measurements made at the Edgewater boiler. Thermal predictions were matched to give reasonable agreement with the measured temperatures in the upper furnace at test load. The calibrated model was then used to predict the gas temperatures for three test cases. These were:

- Full load corresponding to 318,200 kg/hr of steam with old burners and shorter flames
- Full load corresponding to 218,200 kg/hr of steam with staged burners and longer flames taking account of heat removal by jet air dilution and endothermic calcination reactions
- 65 percent load, with staged burners including effect of jet air addition and calcination

The full load and 65 percent load input conditions used in the model are shown in Table 8-1. The full load was defined as the thermal input producing 318,200 kg of steam per hour. At this load, all twelve burners are in operation. The low load test case was run with lower nine burners in operation based on the earlier data obtained from B&W. The effect of the low-NO_x burners was modeled by changing the rate of reaction of the volatile component of the coal to vary the effective flame length. For this purpose, the low-NO_x burners were estimated to produce a flame length of about 5.5 - 6.1 meters based on flame lengths observed from full scale B&W low-NO_x burners in the LWS facility. The flame length for the standard burner was estimated to be 3.7 - 4.3 meters. Figure 8-1 shows contours of unburnt volatiles in the furnace on a vertical plane through the centerline of a row of burners. The contour for one percent unburnt volatiles was taken as representing the effective boundary of the flame zone, although the carbon burnout extends outside this boundary. Figure 8-1 shows the increase in

TABLE 8-1. MODEL INPUT CONDITIONS

Parameter / Load	MCR	65% MCR
No. of Burners in operation	12	9
Coal feed per burner, Kg/hr	2,914.6	2,419.7
Primary air flow per burner, kg/hr @ 60°C	4,993.8	4,327.9
Secondary air flow per burner, kg/hr @ 316°C	25,951.0	22,491.0
Air flow to inactive burners, kg/hr @ 316°C	-	5,190.2
Excess Air Level, %	20	28
Furnace Thermal Input, MW_{th}	277.6	180.4
Gross Heating Value of Fuel, MJ/kg	29.8	29.8



100% Load
Standard
No Injection

100% Load
Low NO_x
Sorbent Injection

65% Load
Low NO_x
Sorbent Injection

Figure 8-1. Unburnt volatiles (percent) in Edgewater furnace.

flame volume between standard and low-NO_x burners in accordance with the flame lengths estimated above.

The temperature profiles at full load with old burners and low-NO_x burners are shown in Figure 8-2 and 8-3 respectively. Temperatures in the main flame region were lower with low-NO_x burners, although temperature levels in the upper furnace were not greatly affected by the longer flames. However, the low-NO_x burner case also included the effect of calcination and jet air dilution. The temperature levels at the lower injection level were about 1316°C (2400°F) for both cases. The upper injectors experienced a temperature of about 1260°C (2300°F) which is believed to be near optimum based on the results from Section 5.0. This is primarily because of the entrainment of the flue gas into the sorbent jet; the temperatures in the jet stay lower than the flue gas temperatures near the jet nozzles.

The temperatures at low load are shown in Figure 8-4. The corresponding flame volume as delineated by the one percent unburnt volatile content is shown in Figure 8-1. The reduced heat input and flame volume resulting from low load operation led to reduced temperatures throughout the boiler. The flue gas temperature at the lower level injectors was about 1180°C (2150°F) whereas the upper jets experienced somewhat lower temperatures.

The overall temperature history of the furnace gases through the high temperature superheater and reheater sections is shown in Figures 8-5 and 8-6 for full and part loads respectively. Figure 8-5 compares the full-load predictions for the standard burners without sorbent injection (i.e. normal operating condition) with the predictions using low-NO_x burners and a two-level sorbent injection scheme. Also shown for comparison is the previous estimate using different fuel and input conditions. The current profile for the standard burners is little different from the previously estimated temperature history. With low-NO_x burners and sorbent injection, the gas temperature downstream of the furnace exit initially falls more rapidly, because of the thermal impact of the cold air mixing and the heat needed for calcination. Upstream of the injection points, there was not a big impact from the low-NO_x burners on thermal history. Figure 8-6 shows the

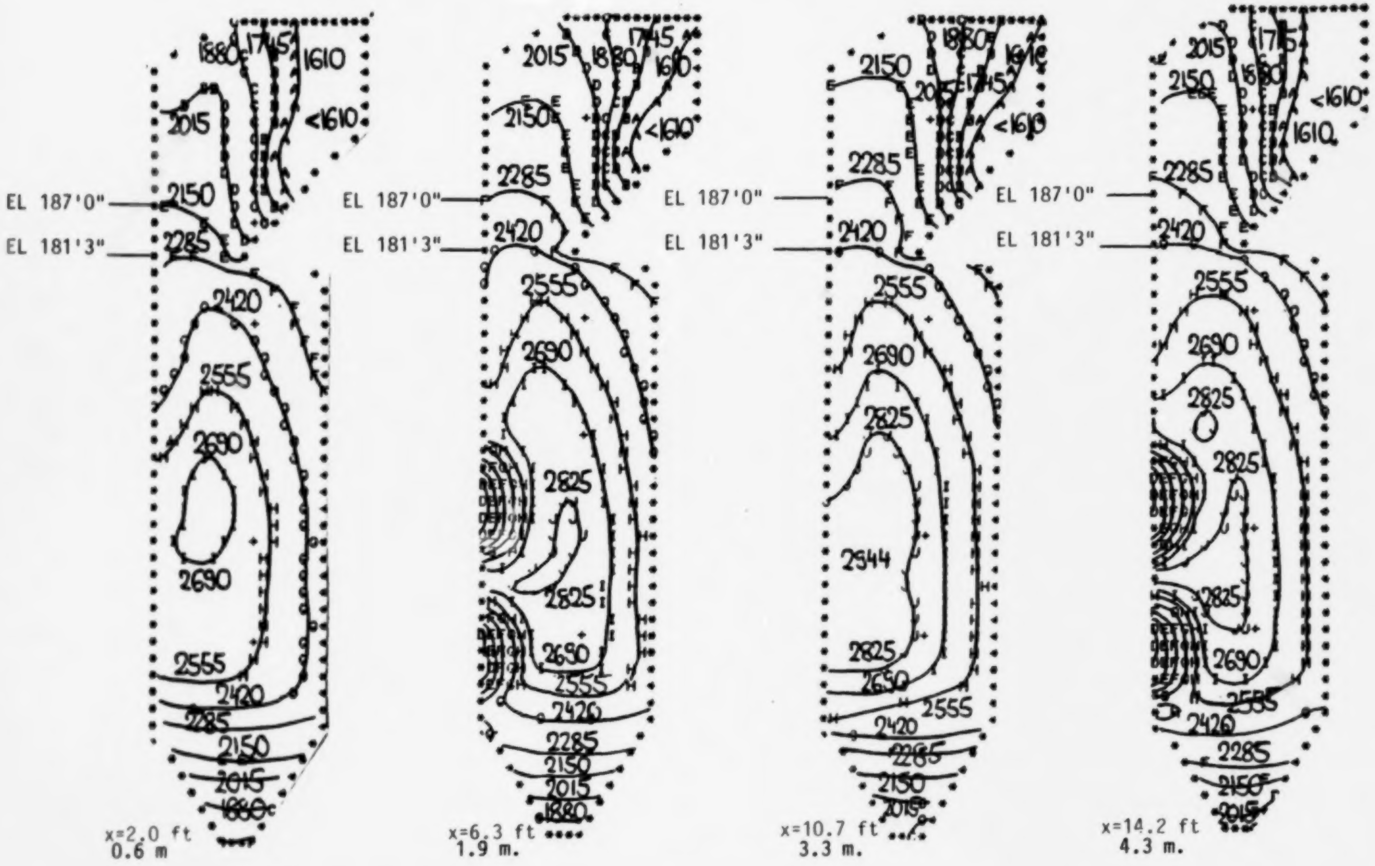


Figure 8-2. 100% load, standard burner, no sorbent injection, 318,200 kg/hr (700,000 lbs/hr) steam, 20% excess air.

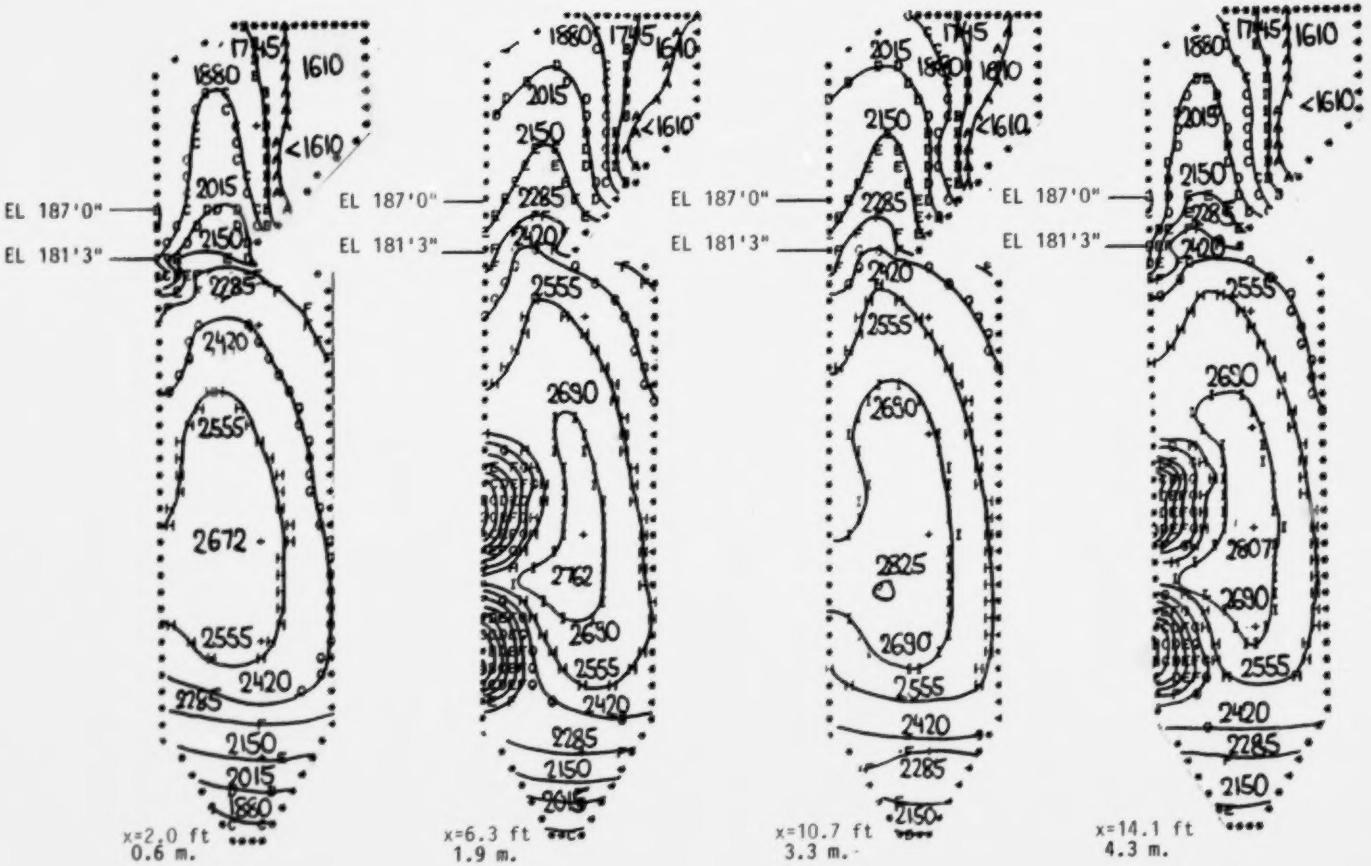


Figure 8-3. 100% load, low NO_x burners, sorbent injection.

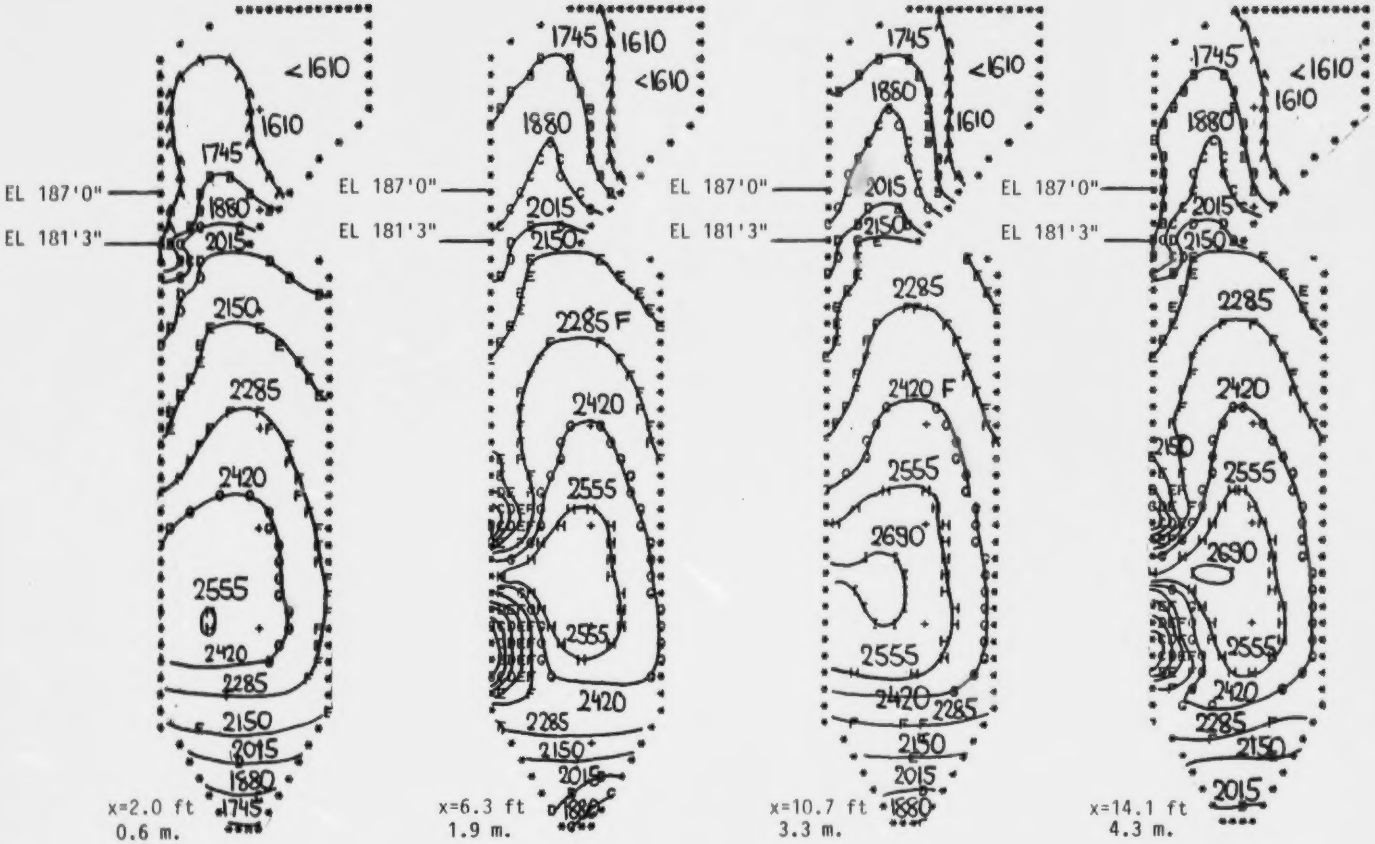


Figure 8-4. 65% load, low NO_x burners, sorbent injection.

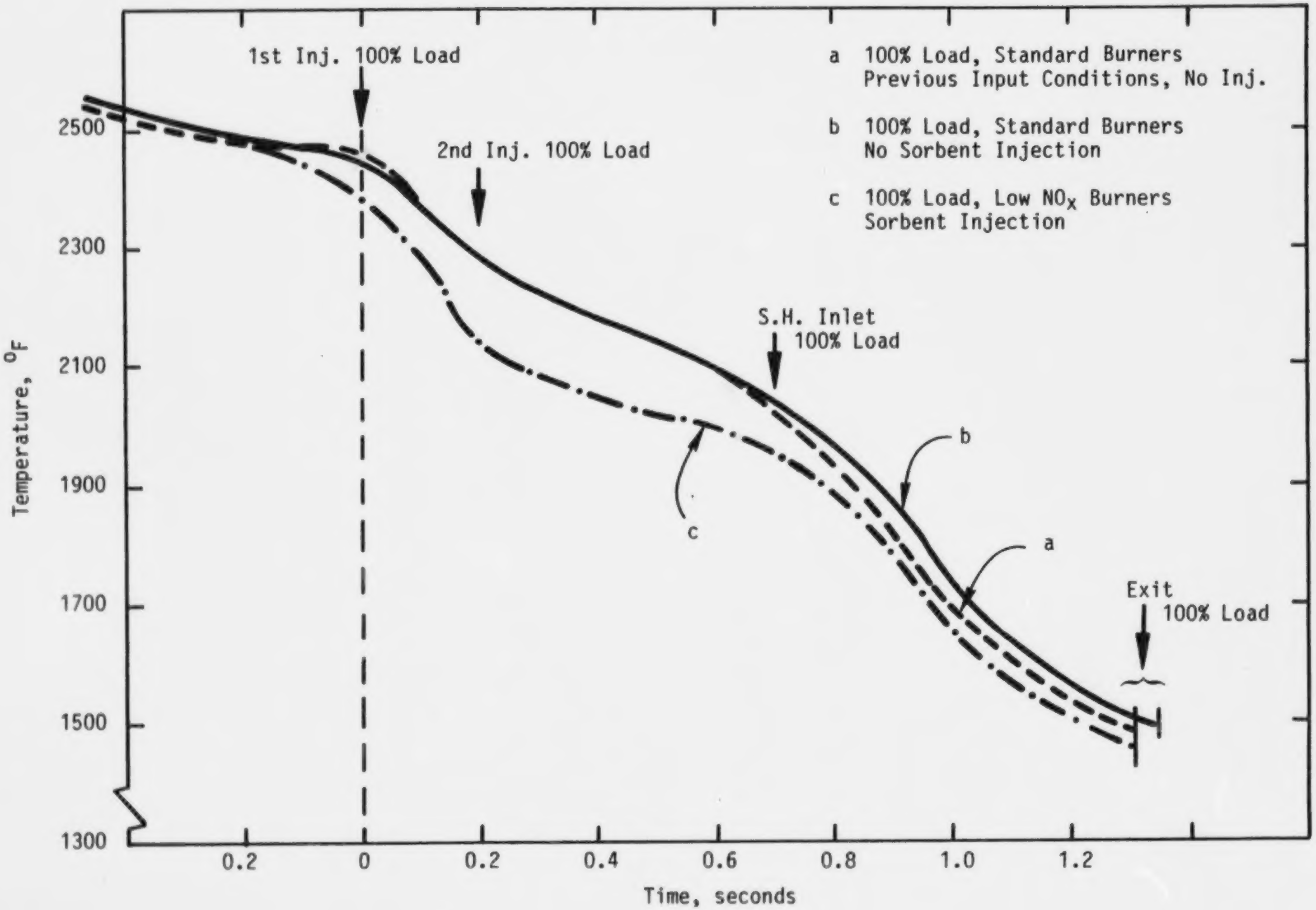


Figure 8-5. Predicted temeprature history in upper furnace region of Edgewater boiler at full-load.

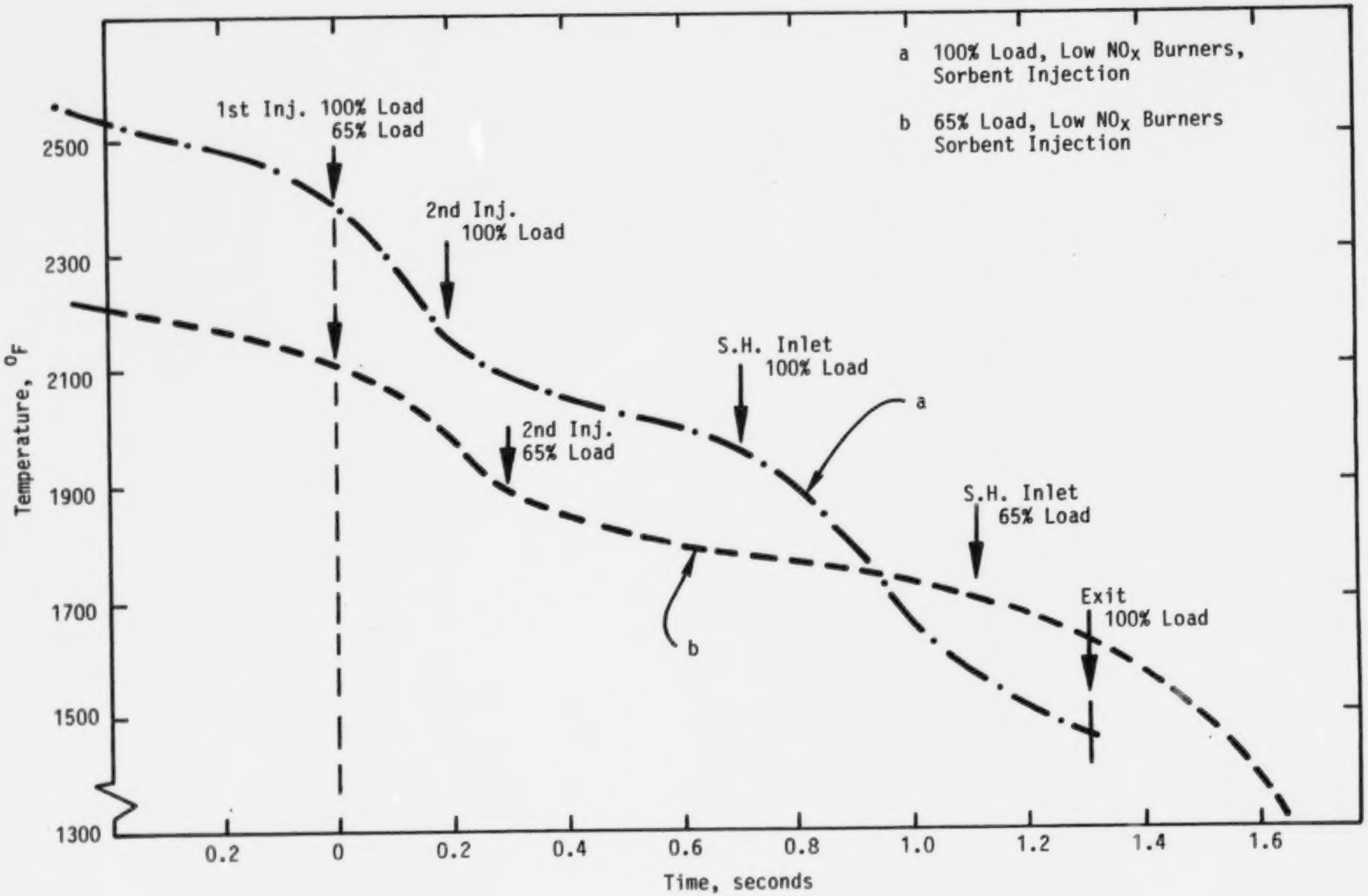


Figure 8-6. Predicted temperature history in upper furnace region of Edgewater boiler: comparison between full and part load.

temperature history at reduced load compared with full load. In both cases the thermal effect of the dilution air and the heat of calcination of the sorbent has been included. As expected, the low load case had lower temperature levels and longer residence time. The temperature at the upstream injection level was reduced from 1316°C (2400°F) to 1150°C (2100°F) and the residence time in the temperature window from 1230°C (2250°F) to 870°C (1600°F) was extended from 1.07 seconds to 1.23 seconds (downstream of the first injection point).

For the purposes of making sulfur capture estimations, these predictions of furnace thermal environment were approximated by the piecewise linearization shown in Figure 8-7. This excluded the cooling effect of the injection air because that was included later in the jet heat up calculations. The 220°C/sec (400°F/sec) quench rate corresponded to the region between the nose plane and the entrance to the first bank of superheaters. The temperatures declined at a much higher rate as the flow passed through the superheater sections. No sulfur capture estimations were made for the reduced load case.

8.2 Isothermal Modeling

Isothermal modeling of a wide variety of boilers has provided insight into general boiler and upper furnace flows. These were used as the basis of the flow field input to GBTAC. Isothermal modeling of Edgewater alone under contract to B&W has confirmed the validity of the assumed GBTAC input flows.

Isothermal modeling of jets injected into the upper furnace region was performed on both the Edgewater Upper Furnace Cell in this program and separately in the Edgewater boiler model for B&W. These tests were the basis of selecting the jet configurations chosen for the demonstrations. Figures 8-8 and 8-9 show smoke visualization sketches of jets for two of the more relevant cases. The first was the case with 8 jets of 9.0 cm (3.55") dia. on the front wall at EL 181'3" injected with a momentum flux ratio J = 100. This was the original configuration defined by B&W for Edgewater. Figure 8-9 shows the two level configuration with 8 front wall and 2 side wall jets of

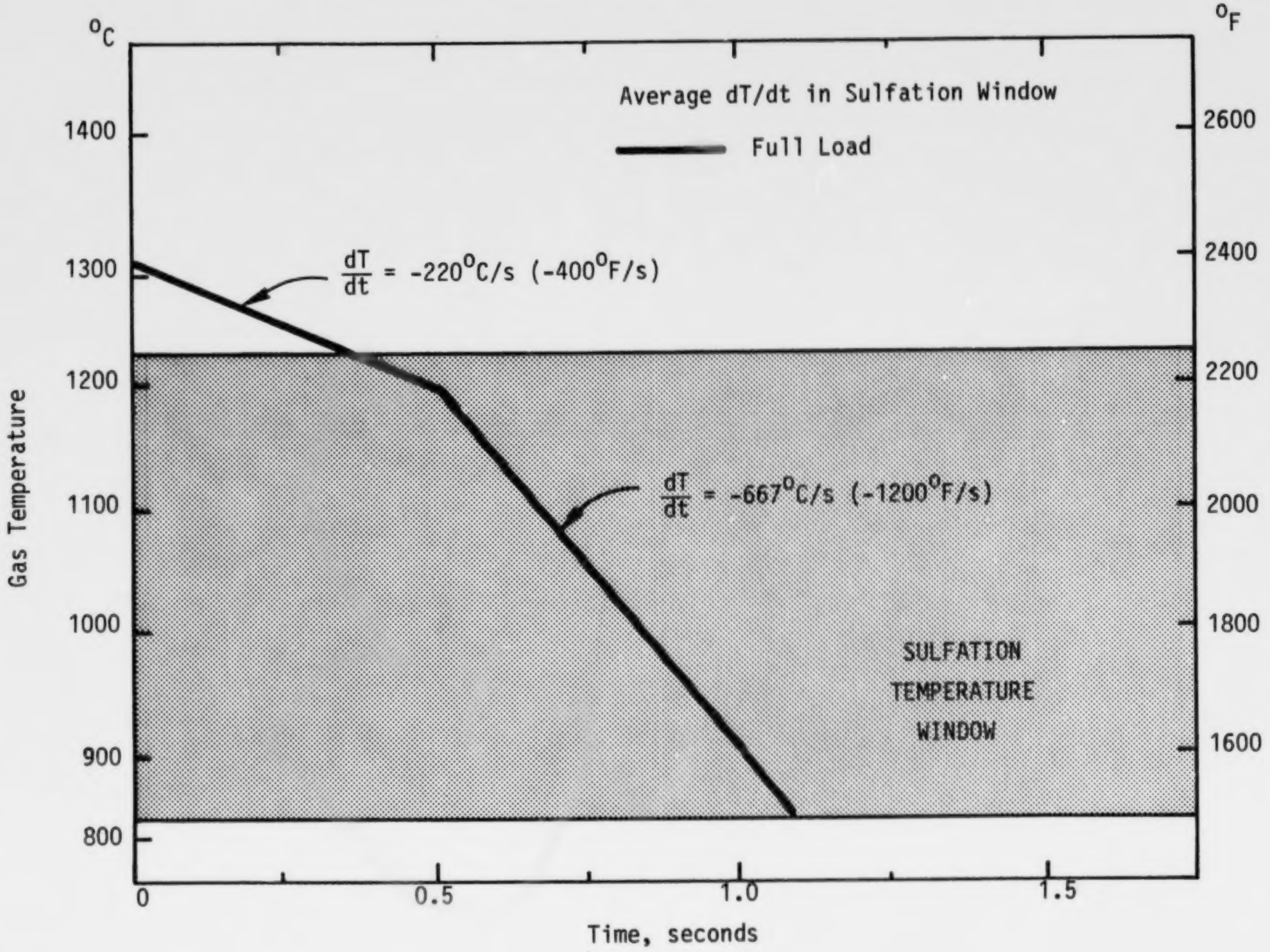


Figure 8-7. Edgewater boiler time/temperature profile used in capture estimations.

Elevation	Ports	J
181'3"	8	100

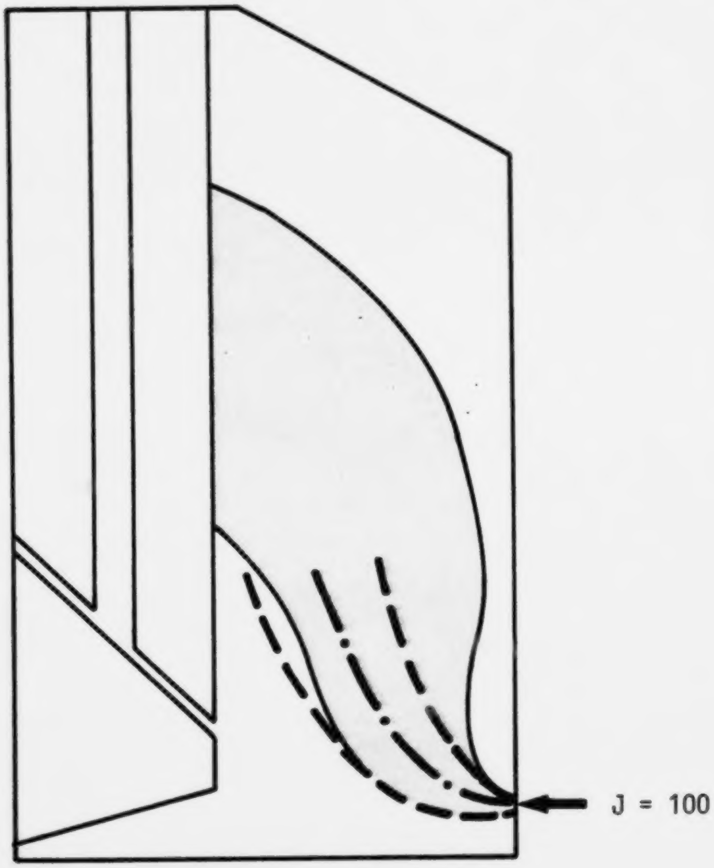


Figure 8-8. Smoke visualization of sorbent injection jets in Edgewater boiler model: single level injection.

Elevation	Ports	J
181'3"	10	100
187'0"	12	50

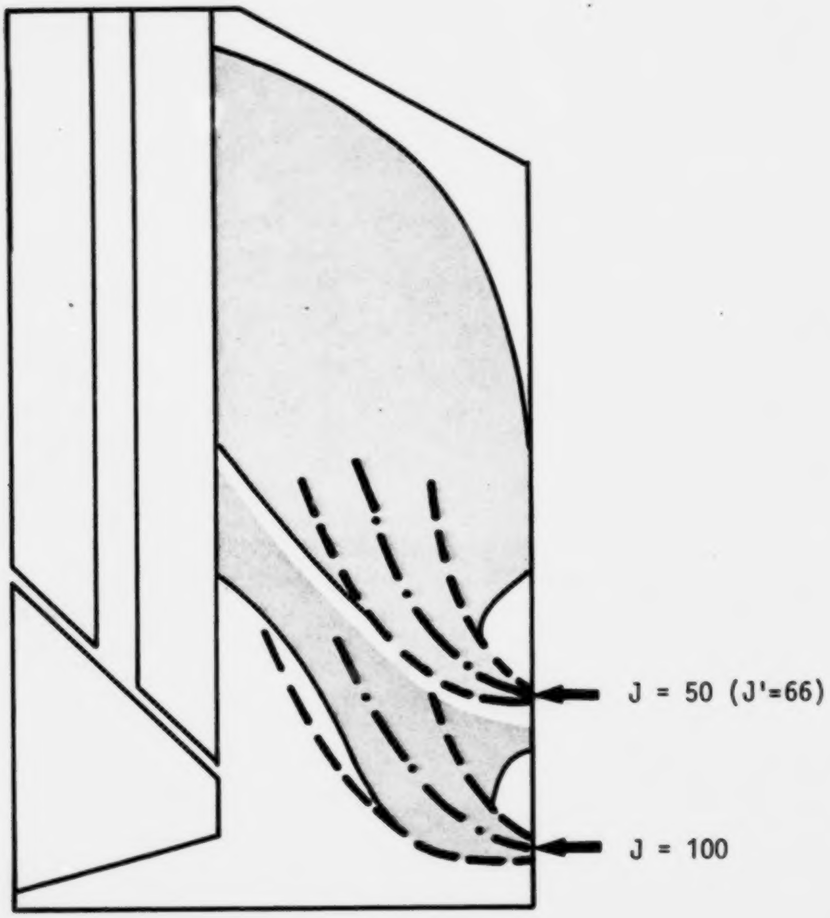
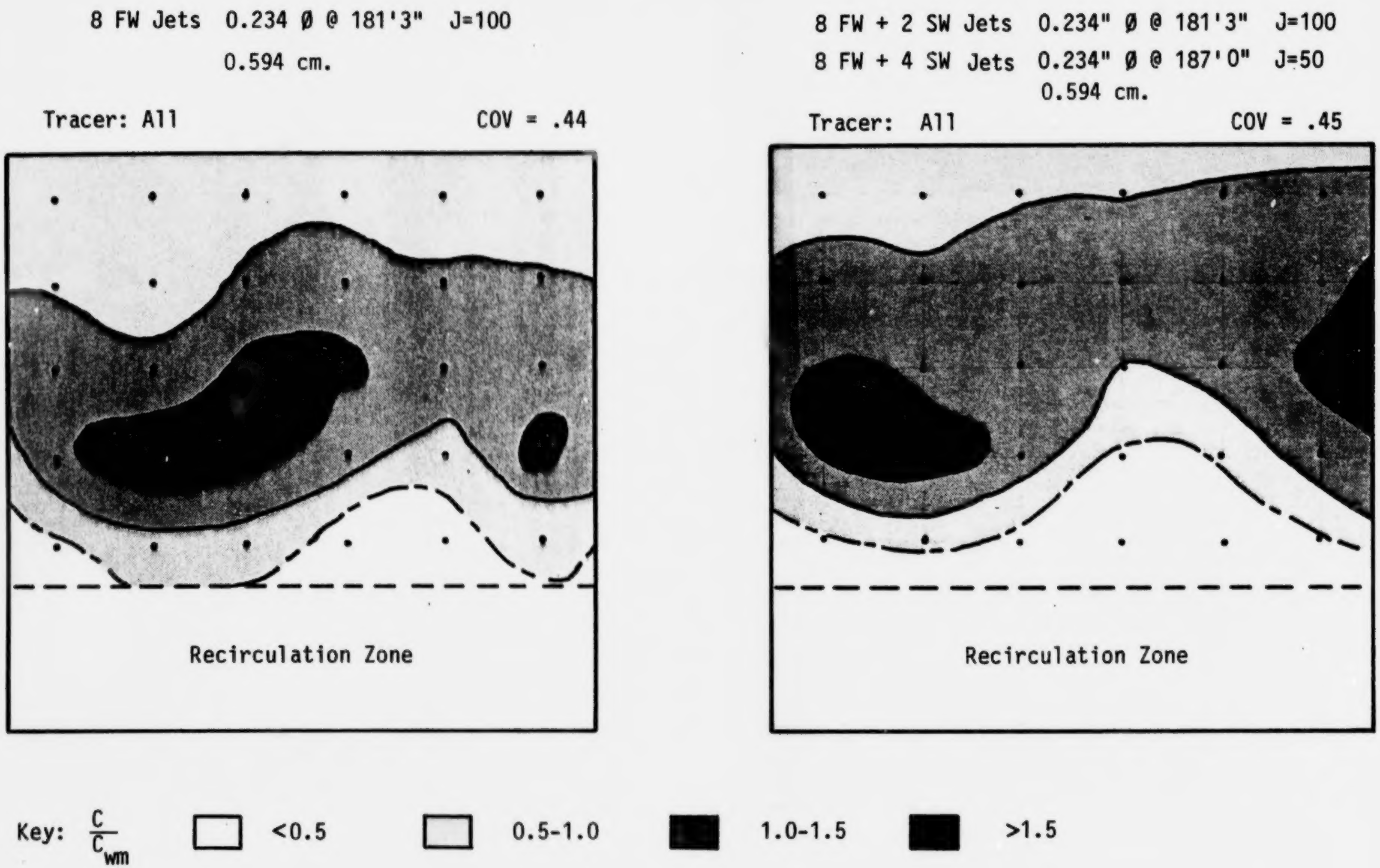


Figure 8-9. Smoke visualization of sorbent injection jets in Edgewater boiler model: 2 level injection.

9.0 cm (3.55") dia. at J = 100 at EL 181'3" combined with 8 front wall and 4 side wall jets of 9.0 cm (3.55") dia. at J = 50 at EL 187'0". Superimposed on the observed smoke trajectories are the predicted trajectories and jet widths using the jet model JICFIS. These show good agreement close to the jet nozzle, but the observed smoke path broadens more rapidly on the downstream side of the jet because of the fluid that is entrained into the wake of the jet. In the two level injection scheme, Figure 8-9, the upper jets were observed to penetrate more than they would be expected for its nominal momentum flux ratio. This was because the upper jets experienced a reduced velocity in the wakes of the lower jets. By matching trajectories and jet widths obtained from the jet model JICFIS with the smoke pattern, it appeared that the upper jets behaved as though they had a momentum flux ratio of J = 66 instead of J = 50. This corresponded to a reduced crossflow velocity of 12.8 m/s (42 ft/s) compared to 14.9 m/s (49 ft/s) for the lower jets.

The dispersion patterns measured at the superheater inlet plane for these two injection configurations are shown in Figure 8-10. Although slightly different in details, both injection schemes produced similar deviations from the perfectly uniform concentration profile as indicated by nearly equal coefficient of variations (COV) of about 0.45.

The total transport air requirements for injection schemes are summarized in Table 8-2. Case 1 corresponded to the injection configuration with 22 nozzles at two injection levels. The total injection air requirement for this case was 7.8 percent of the total combustion air. Case 2 was the 8 jets located near the nose with a total injection air requirement of 3 percent of total combustion air. Also given in Table 8-2 for these cases is the total jet mass flow (transport air plus sorbent) as a percentage of the total flue gas flow through the upper furnace. This figure provides a measure of the amount of jet entrainment needed to achieve reasonable dispersion of the sorbent into the flue gas. Case 1, with a jet mass flow of 8.4 percent, would require about 12 jet mass flows of entrainment, whereas the the empirical design option, Case 2, has a jet mass flow of 4 percent and would require about 25 jet mass flows of entrainment. Thus, the 22 jet


8 FW Jets 0.234 Ø @ 181'3" J=100
0.594 cm.

Tracer: All COV = .44

8 FW + 2 SW Jets 0.234" Ø @ 181'3" J=100
8 FW + 4 SW Jets 0.234" Ø @ 187'0" J=50
0.594 cm.

Tracer: All COV = .45

Key: $\frac{C}{C_{wm}}$ ☐ <0.5 ▨ 0.5-1.0 ■ 1.0-1.5 ■ >1.5

Figure 8-10. Contour plots for injection schemes.

TABLE 8-2. SUMMARY OF JET INJECTION FLOWS - EDGEWATER BOILER

Case	Injection Level	No. of Jets	Jet Diameter cm (inch)	J	Jet Velocity m/s (ft/s)	Injection Air kg/s (lb/s)	Inj. Air Percent Comb. Air	Jet Flow* Percent Flue Gas
1	EL 181'3"	10	9.02 (3.55)	100	65.2 (214)	4.35 (9.58)	7.8%	8.4%
	EL 187'0"	12	9.02 (3.55)	50	46.0 (151)	3.69 (8.13)		
2	EL 181'3"	8	9.02 (3.55)	100	58.5 (192)	3.13 (6.89)	3.0%	4.0%

Operating Conditions:

Steam flow	318,200 kg/hr	(700,000 lb/hr)
Coal flow	33,503 kg/hr	(73,706 lb/hr)
Air flow	372,497 kg/hr	(819,493 lb/hr)
Flue gas flow	402.705 kg/hr	(885,951 lb/hr) (minus fly ash).

(*) Jet flow includes sorbent mass

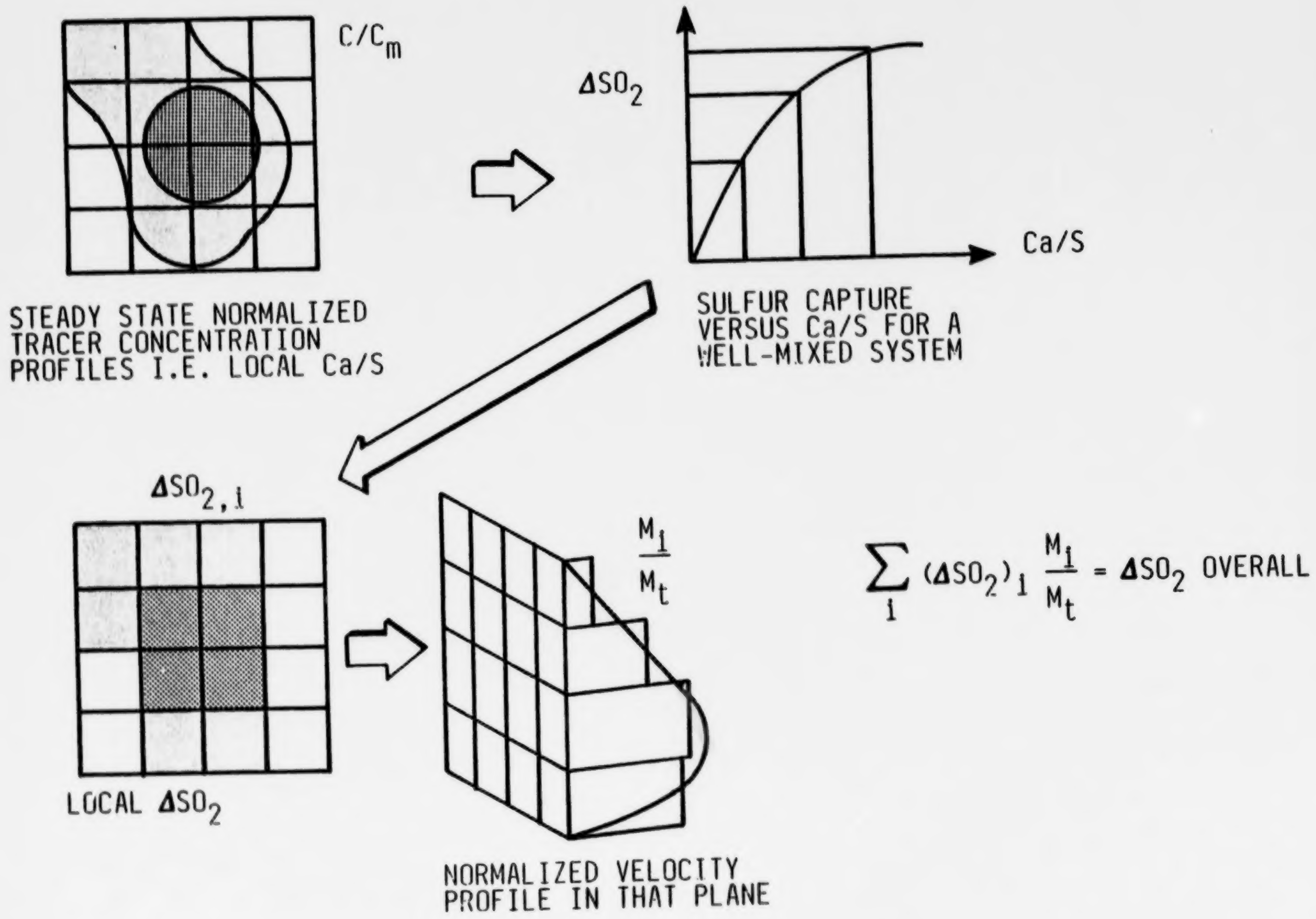
option would potentially achieve more rapid mixing of sorbent into the flue gas, with sorbent concentration and temperature histories likely to give better capture. This is shown in Subsection 8.3.3 which discusses the jet model predictions. Hence, the higher amount of transport air divided into a larger number of jets appears to be a significant advantage from the viewpoint of effective sorbent/gas mixing and is preferable provided the operation of the boiler's combustion system is not compromised.

8.3 Sulfur Capture Predictions

Preliminary estimates of expected sulfur removal efficiency were made based on the procedures and experimental data presented in the preceding sections. Three different approaches were used to estimate sulfur removal efficiencies. First one is described in Section 8.3.1 and involves determining the impact of sorbent mixing and non-uniform flow distribution on sulfur capture utilizing the bench scale experimental data. The second approach is interpretation of pilot scale data obtained under conditions similar to those of Edgewater boiler. Third approach stresses the effects of jet heat-up and dilution using the jet and sulfur capture models. The results of this approach are presented in Section 8.3.3. The effect of down angled roof jets are also discussed in this section.

8.3.1 Sulfur Capture with Proposed Injection Scheme

A simple methodology was employed to estimate the sulfur capture based on the isothermal velocity and dispersion patterns. Figure 8-11 outlines the steps involved in this approach. The steady state tracer concentration profile, obtained for the particular injection scheme, was used to determine local Ca/S distribution which then allowed determination of sulfur capture distribution based on experimental data which were not greatly affected by mixing (i.e. CTT data). Because of the non-uniformity of the mass flow distribution at the dispersion plane, the local sulfur capture distribution was weighted by the mass flow distribution to obtain the overall-sulfur capture. Figure 8-12 shows the CTT data obtained with Linwood AH with three fuels. Two sets of predictions shown later were based on sulfur capture


C/C$_m$
STEADY STATE NORMALIZED TRACER CONCENTRATION PROFILES I.E. LOCAL Ca/S
ΔSO$_2$
Ca/S
SULFUR CAPTURE VERSUS Ca/S FOR A WELL-MIXED SYSTEM
ΔSO$_{2,i}$
LOCAL ΔSO$_2$
$\frac{M_i}{M_t}$
NORMALIZED VELOCITY PROFILE IN THAT PLANE

$$\sum_i (\Delta SO_2)_i \frac{M_i}{M_t} = \Delta SO_2 \text{ OVERALL}$$

Figure 8-11. A simple methodology to estimate the sulfur removal efficiency.

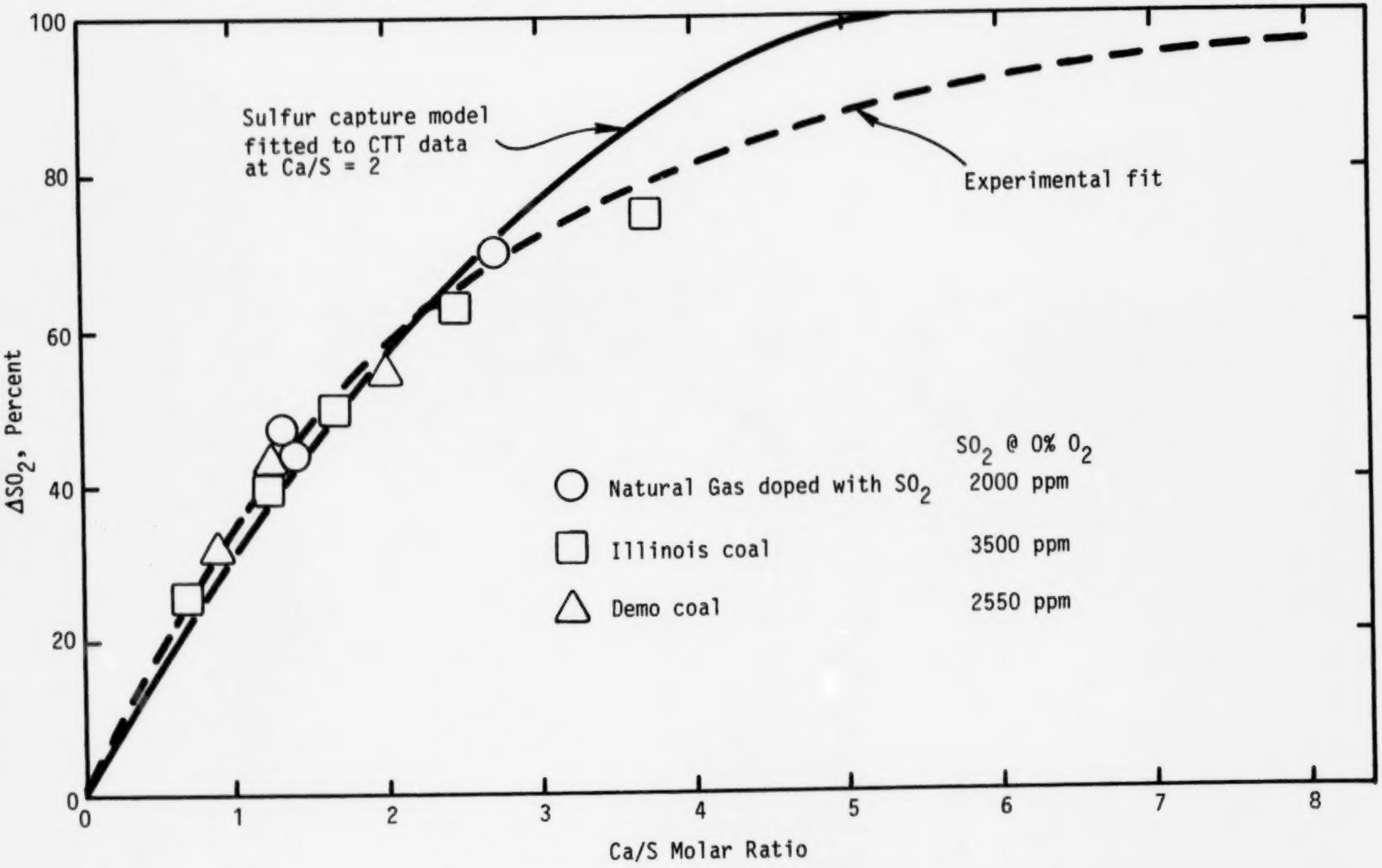


Figure 8-12. Sulfur capture with Linwood AH with different fuels in the CTT furnace.

model data fit and the experimental data fit which differ at Ca/S ratios higher than 3.0. The dispersion and velocity measurement plane considered for the calculation was the oblique plane joining the nose to the upper corner of the furnace front wall where gas temperatures ranged between 1150°C (2100°F) and 1200°C (2200°F) at full load. Selection of this location was based on the good agreement obtained between measurements and similar predictions done for the pilot scale combustion tests described in Section 5.0. The normalized velocity profile at this plane is shown in Figure 8-13. Similarly, the contour plot of tracer concentrations at the same location is shown in Figure 8-14. This tracer profile was obtained for the injection configuration with 8 front + 2 side 9.0 cm (3.5") dia. nozzles at elevation 181'3" operating at J = 100 and 8 front + 4 side 9.0 cm (3.5") dia. nozzles at elevation 187' operating with J = 50.

The procedure summarized in Figure 8-11 was applied to the data. Figure 8-15 shows the sulfur capture data which are believed to be reasonable estimates for Edgewater boiler based on the current information. Two sets of predictions were made for the two data fits shown in Figure 8-12. Because of the different temperature quench rates for the CTT furnace and Edgewater boiler, a quench rate correction was applied based on the sulfur capture model using the estimated temperature histories. The effect of dispersion was superimposed on the quench-rate-corrected data to obtain the predictions. The two sets of predictions are similar at low Ca/S molar ratios and differ slightly at Ca/S > 2.0. At Ca/S = 2, the sulfur capture was predicted to be around 45 percent for Linwood AH. A similar exercise was done for Marblehead atmospheric hydrate. The results are shown in Figure 8-16. The expected capture level is slightly below 40 percent at Ca/S = 2.0.

8.3.2 Sulfur Capture from Tower Tests

In addition to the above interpretation scheme, sulfur capture data from dispersion tower tests were available for the Edgewater boiler upper furnace geometry under similar operating conditions. Figure 8-17 shows the results obtained with the injector configuration corresponding to eight 9.0 cm (3.5") dia. nozzles on the front wall at the nose level. The same interpretation

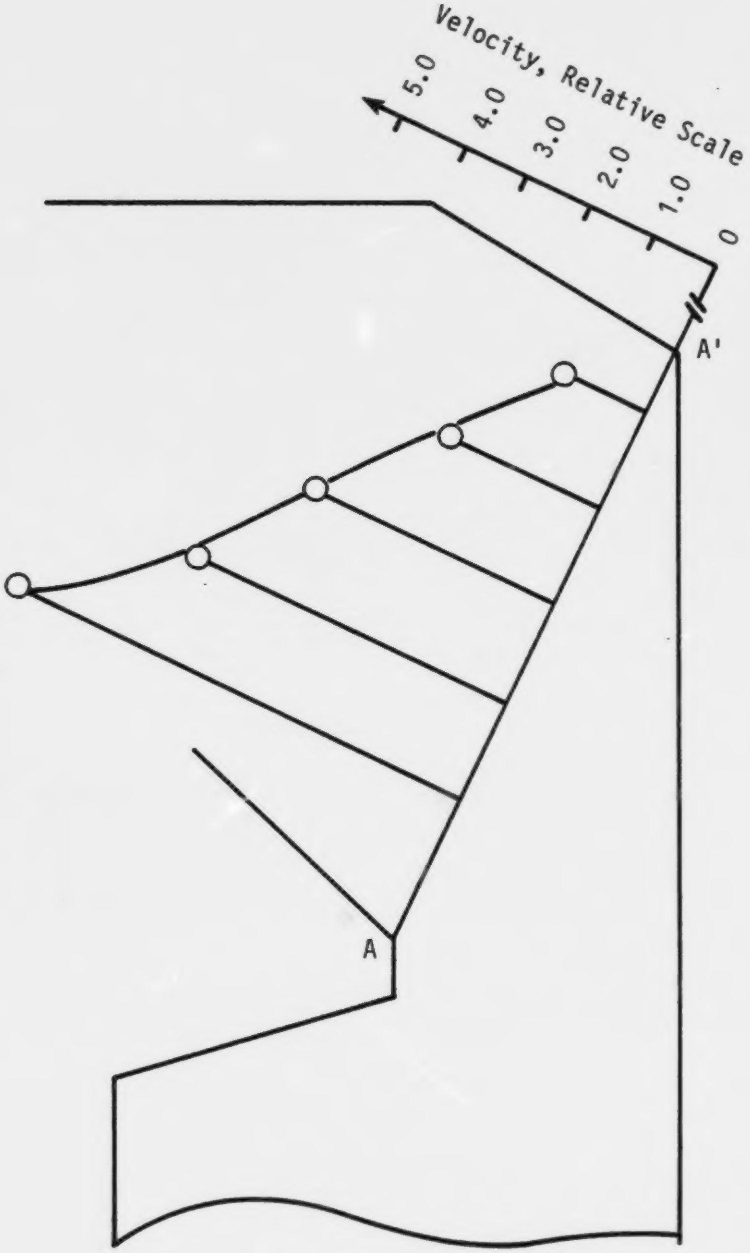
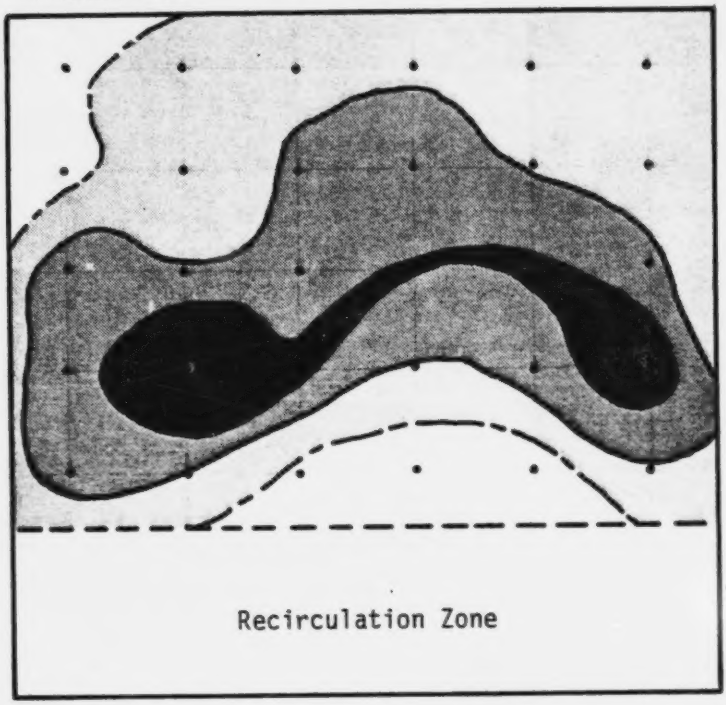

Velocity, Relative Scale
5.0
4.0
3.0
2.0
1.0
0
A'
A

Figure 8-13. Velocity profile along the concentration measurement plane.

8 FW + 2 FW Jets 0.234" Ø @ 181'3" J=100

8 FW + 4 FW Jets 0.234" Ø @ 187'0" J=50

Tracer: All



Test 4 (e)

Key: $\frac{C}{C_{wm}}$ ☐ <0.5 ▨ 0.5-1.0 ■ 1.0-1.5 ■ >1.5

Figure 8-14. Steady state tracer concentrations at the alternate measurement plane.

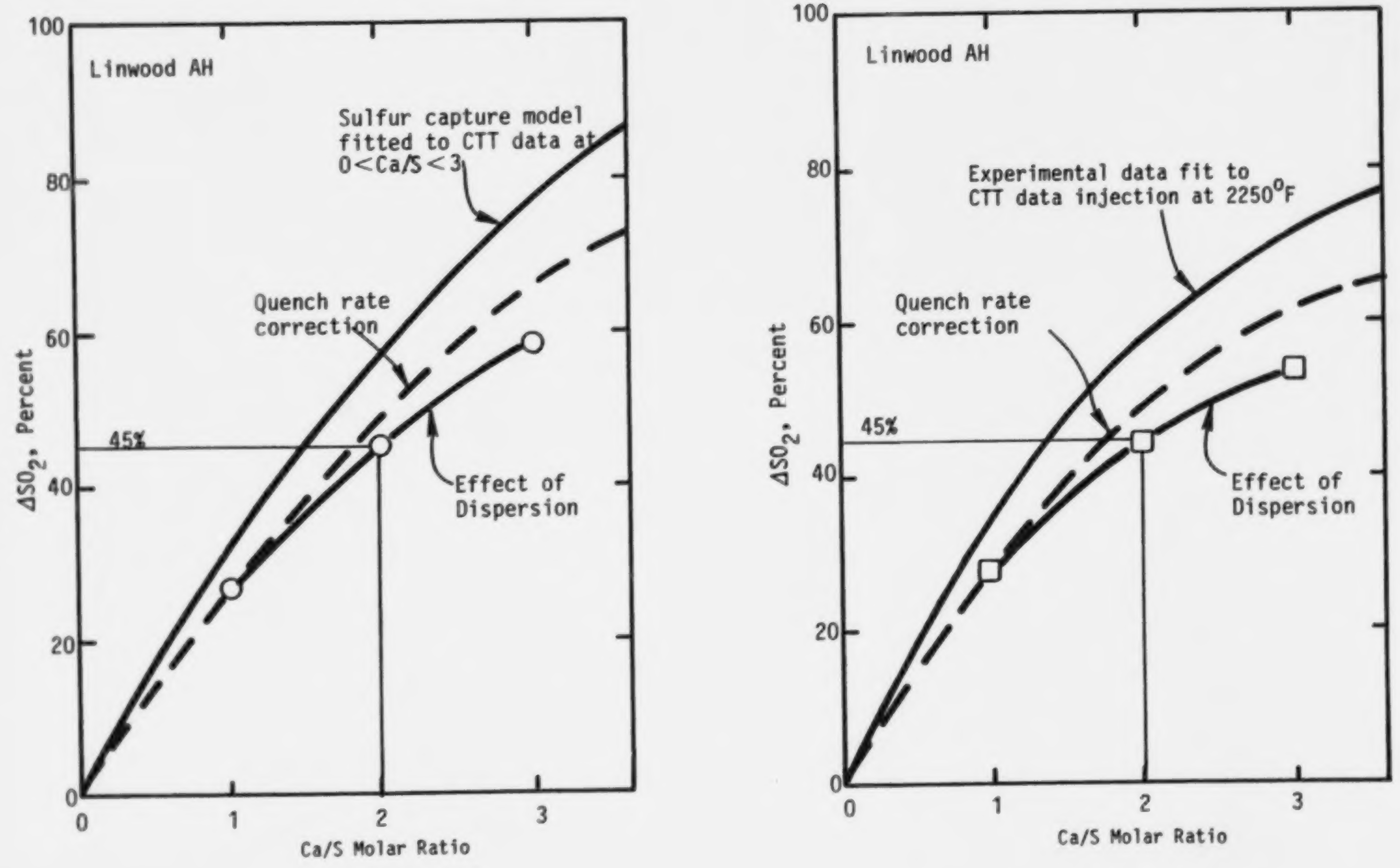


Figure 8-15. Estimated sulfur capture at Edgewater boiler with B&W injection scheme with Linwood AH.

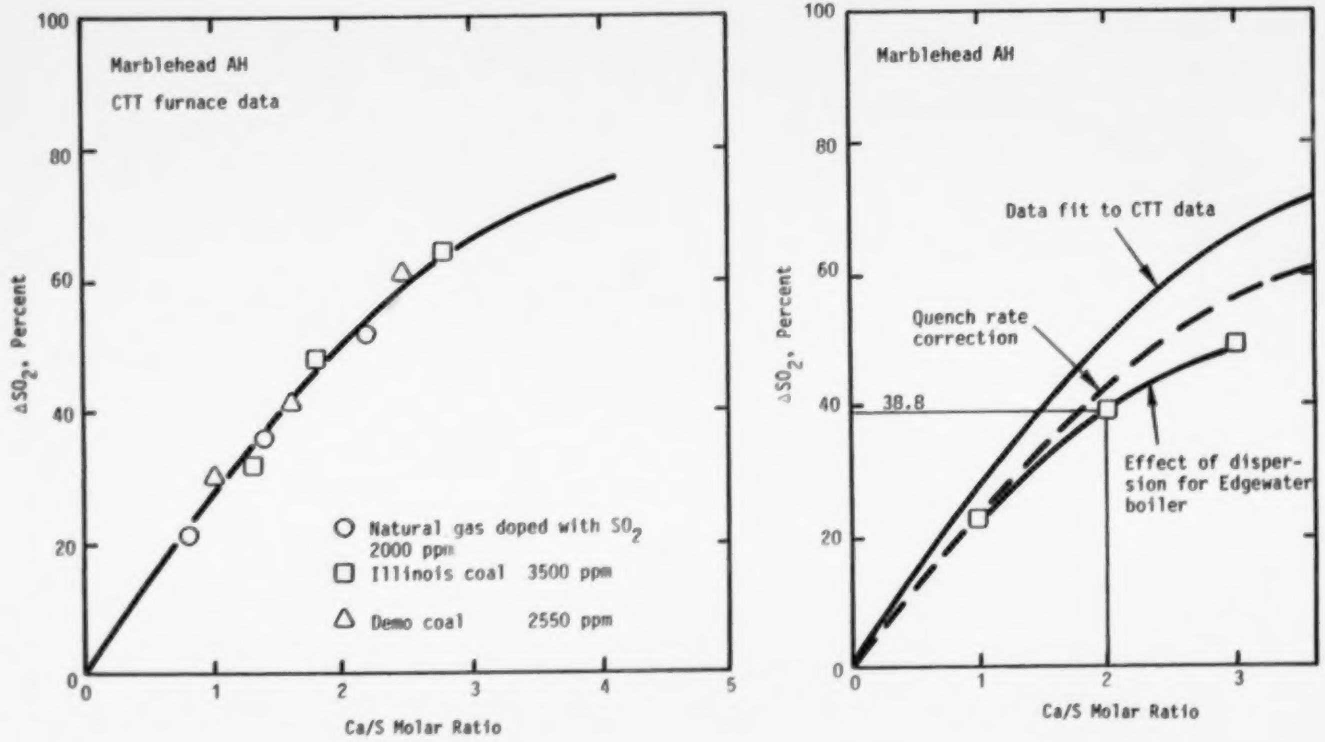


Figure 8-16. Estimated sulfur capture at Edgewater boiler with B&W injection scheme with Marblehead AH.

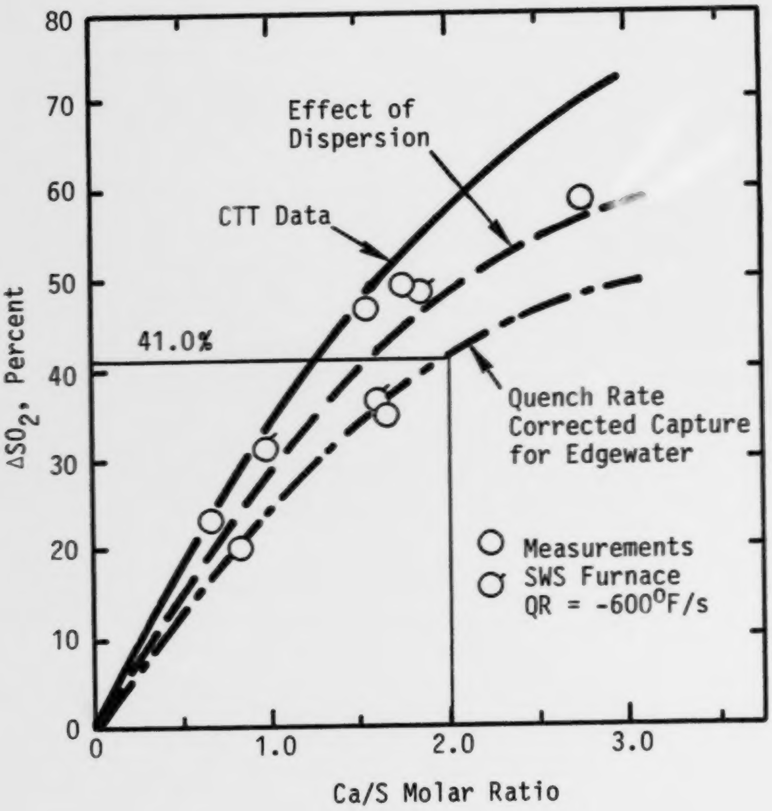


Figure 8-17. Sorbent injection data from SWS for the case corresponding to 8-3.5" Ø nozzles near the nose elevation with J ≈100 and Linwood atmospheric hydrate.

scheme was used to explain the impact of dispersion for these tests. Because of the lower quench rate of flue gas in these experiments (-330°C/sec), a quench rate correction was applied to infer the sulfur capture at Edgewater boiler. The estimated sulfur capture at Ca/S = 2.0 was about 41 percent based on these results.

8.3.3 Jet Modeling and Sulfation Prediction

In this part, sulfur capture predictions were made by combining predictions of mixing in jets in crossflow with sorbent sulfation modeling. This process is outlined schematically in Figure 8-18. The first step in this approach is to use the JICFIS jet model to calculate centerline trajectory, jet width, mass entrainment and flow time along the jet centerline for the jet and crossflow parameters for the injection case under consideration. The temperature and concentration histories are then obtained by applying energy and mass balances in the jet in conjunction with the jet entrainment and time data and the temperature history (quench rate data) for the flue gas in the upper furnace. The results of these calculations are the temperature and concentration histories of the sorbent within the boundary of the jet. This becomes the input data to the calcium sulfation model which calculates sulfation of calcium particles suspended in a gas having time varying temperature and SO_2 concentration. Because the jet contains all the sorbent within its boundary, this sulfation calculation provides an estimation of the overall sulfur capture of the jet system being considered.

This method was applied to several situations relevant to the Edgewater boiler injection system. The first was the single level system of 8 x 9.0 cm (3.5") jets at J = 100 injected from the front wall at EL 181'-3" (case 2 in Table 8-2). The effects of angling these jets 30° down from the horizontal was also considered, as well as the effect of injecting these angled-down jets from a higher elevation on the wall. Finally, the twenty-two jet injection configuration with 9.0 cm. (3.55") diameter jets injected from two levels on the front wall was studied.

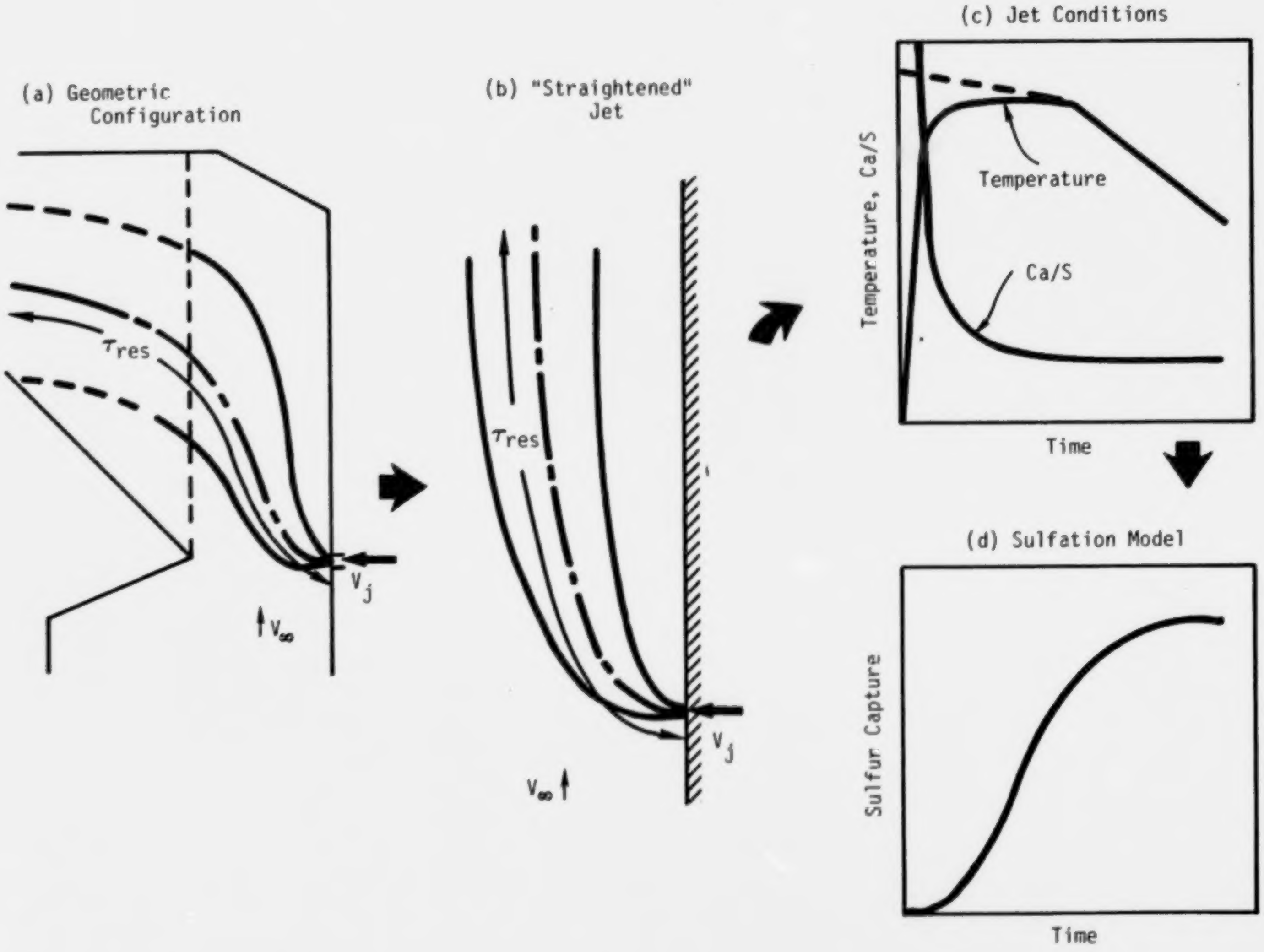

(a) Geometric Configuration
τ_{res}
V_j
V_∞
(b) "Straightened" Jet
τ_{res}
V_∞
V_j
(c) Jet Conditions
Temperature, Ca/S
Temperature
Ca/S
Time
(d) Sulfation Model
Sulfur Capture
Time

Figure 8-18. Schematic of procedure for sulfur capture modeling.

8.3.3.1 Single Level Injection

The results for the single level injection scheme are shown in Figure 8-19 for Linwood A.H. at Ca/S = 2.0. The upper graph shows the temperature and concentration histories for the jet, and the lower figure shows the predicted sulfur capture as a function of time. The jet temperature is seen to rise rapidly initially and then more slowly approaching the surrounding gas temperature. The jet takes about 0.4 seconds to reach its maximum temperature, which is about one-third of the available time in the sulfation temperature window. The peak temperature reached by the jet is 1213°C (2215°F), compared to the injection temperature of 1315°C (2400°F). The calcium-to-sulfur ratio falls from an initial level of greater than 25 towards its well-mixed value of Ca/S = 2.0 over a period of slightly more than 0.5 seconds. The corollary of this is that the concentration of SO_2 around the particles (in the absence of sulfation reaction) rises slowly from zero toward its well-mixed value over the same time. Thus, these jets take about half of the available residence time in the sulfation window to achieve full mixing of the sorbent.

The lower graph shows the progress of sulfation under these conditions. Sulfation rises toward a maximum value at the end of the available time. The notable aspect of this curve is the region in the jet where the rate of sulfation is zero and the overall capture remains constant. This occurs because the temperature and SO_2 concentrations in that region are in a range where calcium sulfate is not stable (the equilibrium constraint) and reaction cannot proceed. It is likely that sulfur capture would be improved if the peak sorbent temperature was lower, in this case below 1180°C (2150°F).

The prediction of sulfur capture as a function of calcium-to-sulfur ratio is shown on Figure 8-20. Capture increases with increasing Ca:S ratio with a slight non-linearity, typical of results observed in experiments. The predicted capture at Ca/S = 2.0 is 49 percent. This is of the same order of the predictions from other approaches, but somewhat higher. In view of the assumptions and uncertainties currently involved in this modeling approach, this seems a commendable result. However, it should be viewed with caution

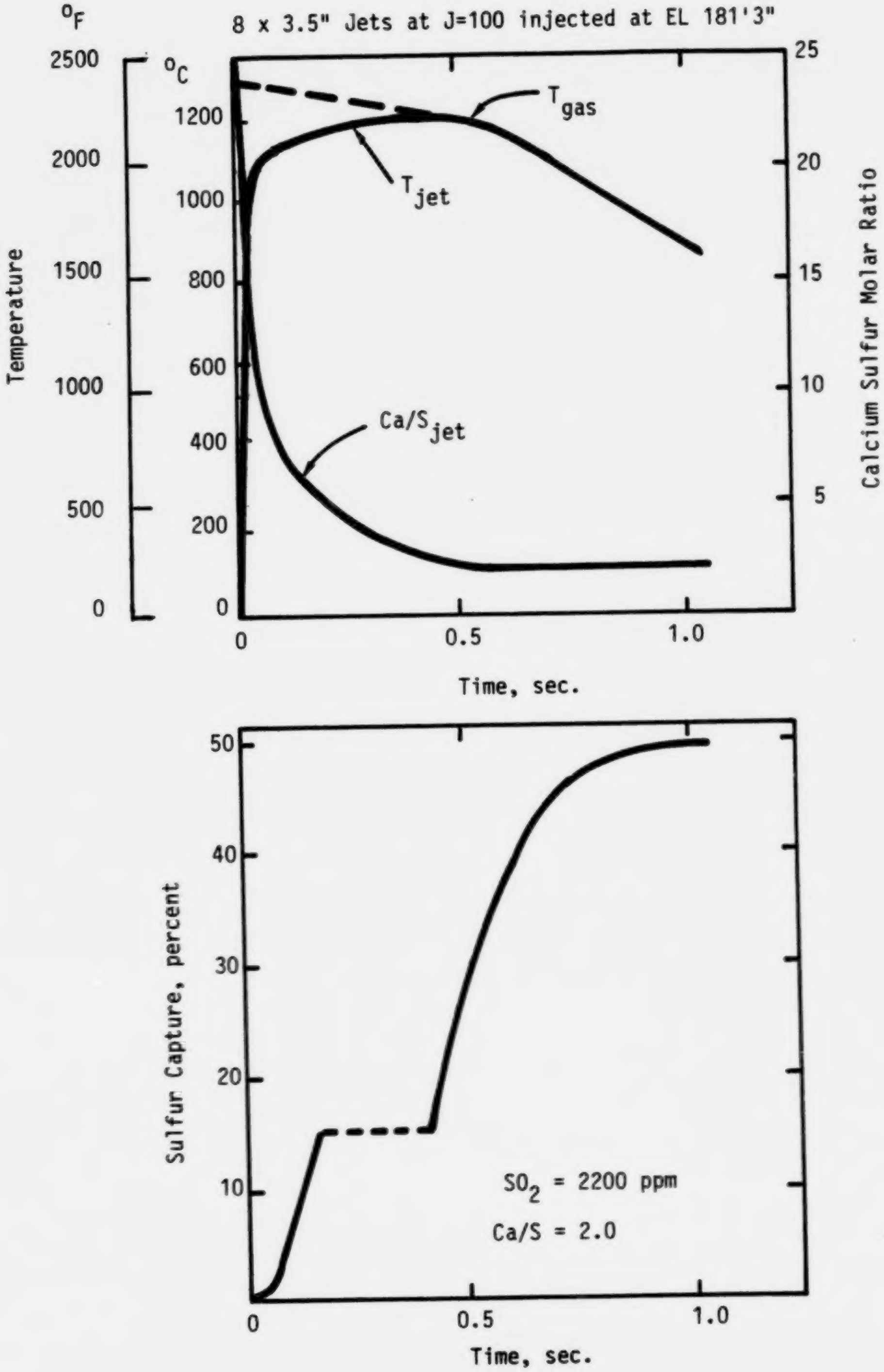


Figure 8-19. Temperature, Ca/S and sulfation predictions.

8 x 3.5" Ø Jets at J = 100 Injected at EL 181'-3"

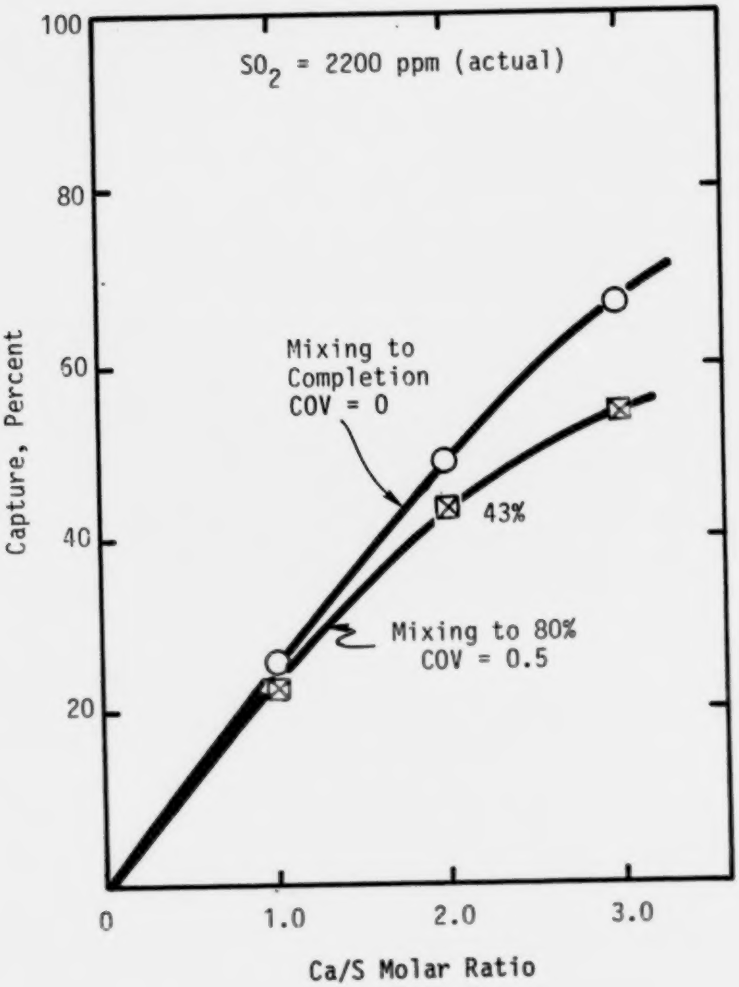


Figure 8-20. Sulfur capture predictions for Edgewater boiler using JICFIS jet model and sulfation model.

and used as an indication only of the likely maximum sulfation that might be achieved. For example the mixing part of the model assumes that the jets entrain until the flue gas has been fully entrained, which implies perfect dispersion of sorbent jets within the furnace flow. However, this is unlikely to happen in practice and a certain fraction of the SO_2 will not be exposed to the sorbent. Thus, a correction to this result to account for inadequate dispersion was required. The isothermal model dispersion measurements gave tracer concentration profiles at the superheater inlet with a coefficient of variation (COV) of about 0.5, which corresponded to sorbent coverage of about 80 percent (i.e. all of the sorbent concentrated into 80 percent of the flue gas with the remaining flue gas seeing no sorbent). This unmixedness could be included in these model predictions by stopping the entrainment process when the jets have entrained only 80 percent of the flue gas instead of proceeding to complete mixing. Thus, it is implied that the mixing stops and the sorbent/gas mixing process is "frozen" at about the point where the flow enters the superheaters.

The results of allowing for incomplete dispersion are also shown in Figure 8-20. The sulfur capture at Ca/S = 2.0 is 43 percent, which is in good agreement with the estimates of sulfur capture for this jet configuration made by other methods.

8.3.3.2 Effect of Angled Jets

Directing jets downward against the upcoming furnace flow offers the possibility of extending the residence time in the high temperature region of the sulfation temperature window. Because of this benefit, the advantages of downward angled jets opposing the furnace flow were explored by studying

- 30° downward angled jets from horizontal injected at the nose elevation, 8 jets 9.0 cm (3.55 inch) diameter jets at a momentum flux ratio of 100.

- 70° downward angled jets from horizontal injected near the roof, 8 jets 9.0 cm (3.55 inch) diameter jets at a momentum flux ratio of 600.

Smoke visualization studies in the isothermal model showed only a slight change in the initial trajectory of the jets when they were angled downward by 30°. The dispersion was similar to that with the horizontal jets. Model predictions from JICFIS confirmed that the trajectory was not greatly changed, but the residence time of the jet in the initial stage was increased by 30 percent.

Figure 8-21 shows the predicted and observed jet paths from the jet model and smoke injection studies for the highly angled jets. The agreement for the jet location and spread is remarkable considering the simple treatment of the jet described in Section 4.0. The piecewise calculation of the jet temperature from an energy balance based on the calculated jet entrainment is also depicted in Figure 8-21. The calculated temperature-time and Ca/S-time profiles for the three jet systems considered are shown in Figure 8-22. Although the moderate angulation of the injection jets at the nose (θ = -30, J = 100) provides longer residence times for sulfation, the highly angled jets in fact have a shorter residence time than the moderately angled jet system. This result can be explained by comparing the transit times in the jet for the three jet systems as shown in Figure 8-23. It can be seen that the flow time in the highly angled jets until they enter the superheater platens is shorter than the corresponding time for the moderately angled jets. This is because of the very high velocities (V_j = 132 m/s, (432 ft/s)) required for penetration of these jets into the opposing furnace flow to achieve penetration in the beginning of the sulfation temperature window. The summary of the sulfur capture predictions with these three injection systems is given in Figure 8-24. In this figure, the three curves, labeled a,b,c show the differences in predicted sulfur capture mainly due to the different time-temperature profiles for the injection systems. Cases (a) and (b) indicate the progress of sulfur capture when the jets at the nose level are horizontal and tilted down by 30° respectively. The temperature at the injection point for these cases is 1316°C. In this case, the effect of

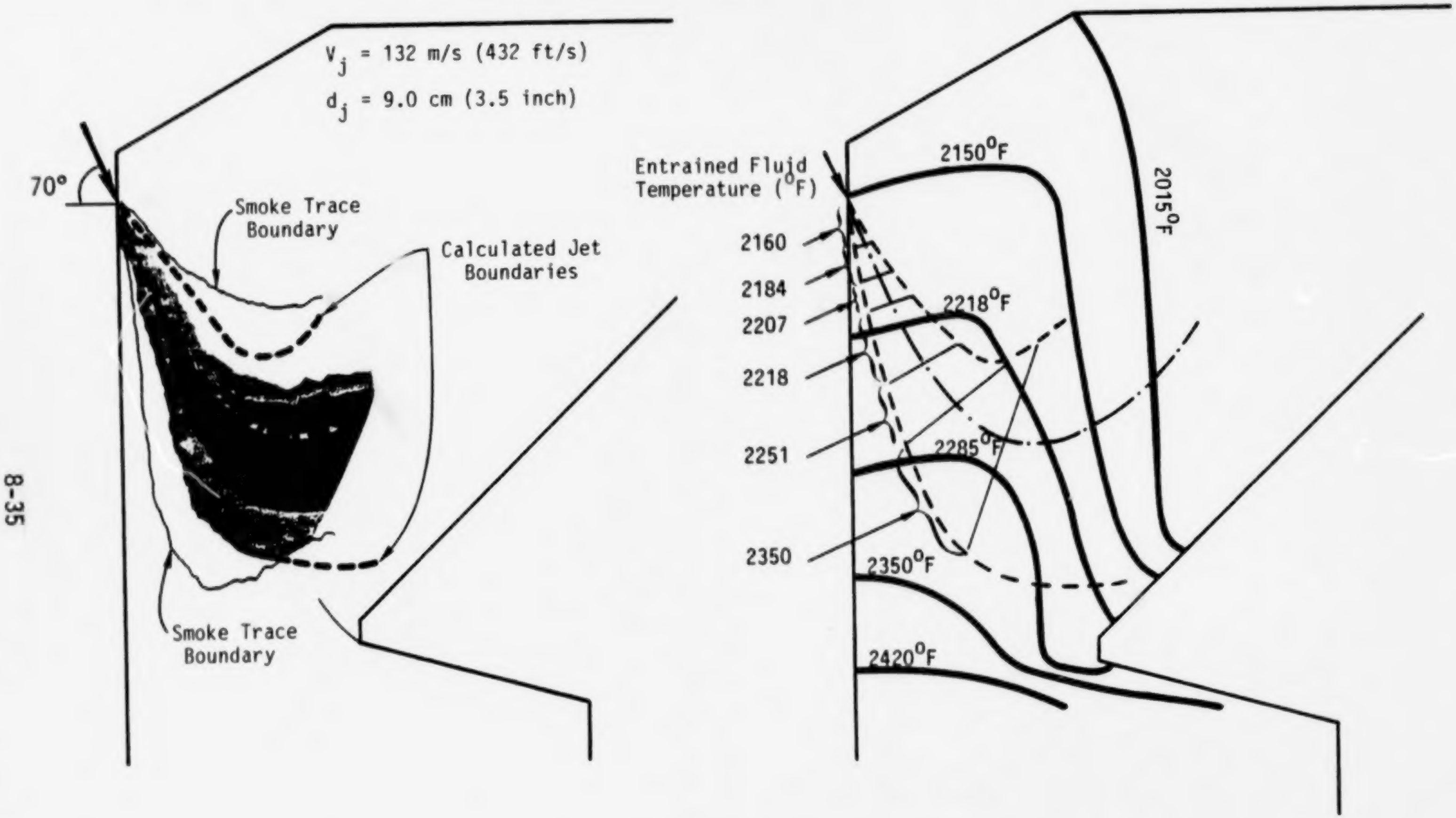

V_j = 132 m/s (432 ft/s)
d_j = 9.0 cm (3.5 inch)
70°
Smoke Trace Boundary
Calculated Jet Boundaries
Smoke Trace Boundary
Entrained Fluid Temperature (°F)
2160
2184
2207
2218
2251
2350
2150°F
2015°F
2218°F
2285°F
2350°F
2420°F

Figure 8-21. Comparisons of calculated and observed jet paths and the piecewise calculation of jet temperatures from calculated entrainment and superimposed furnace temperature profiles.

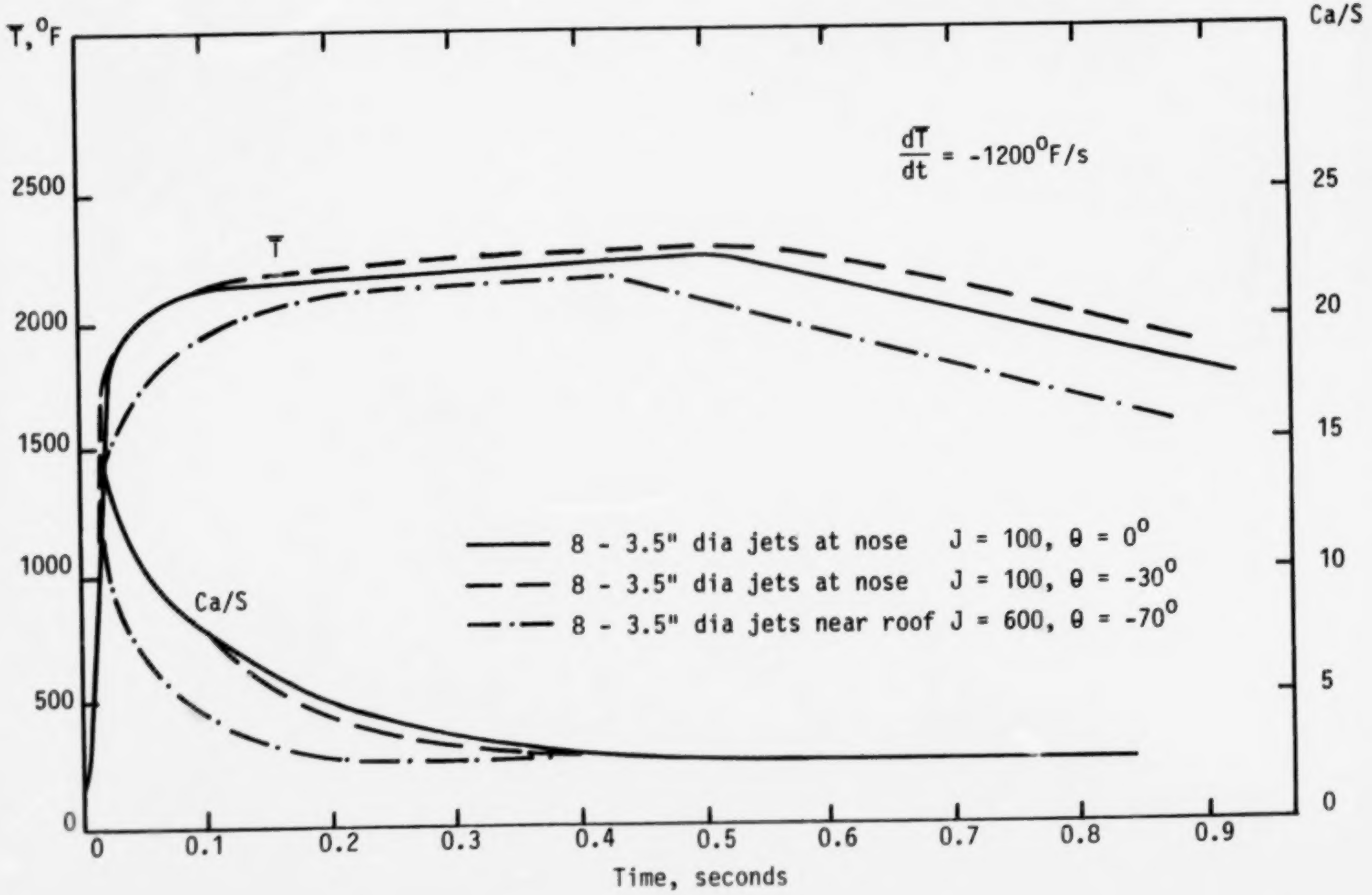


Figure 8-22. Temperature-time and Ca/S-time variations in three jet systems.

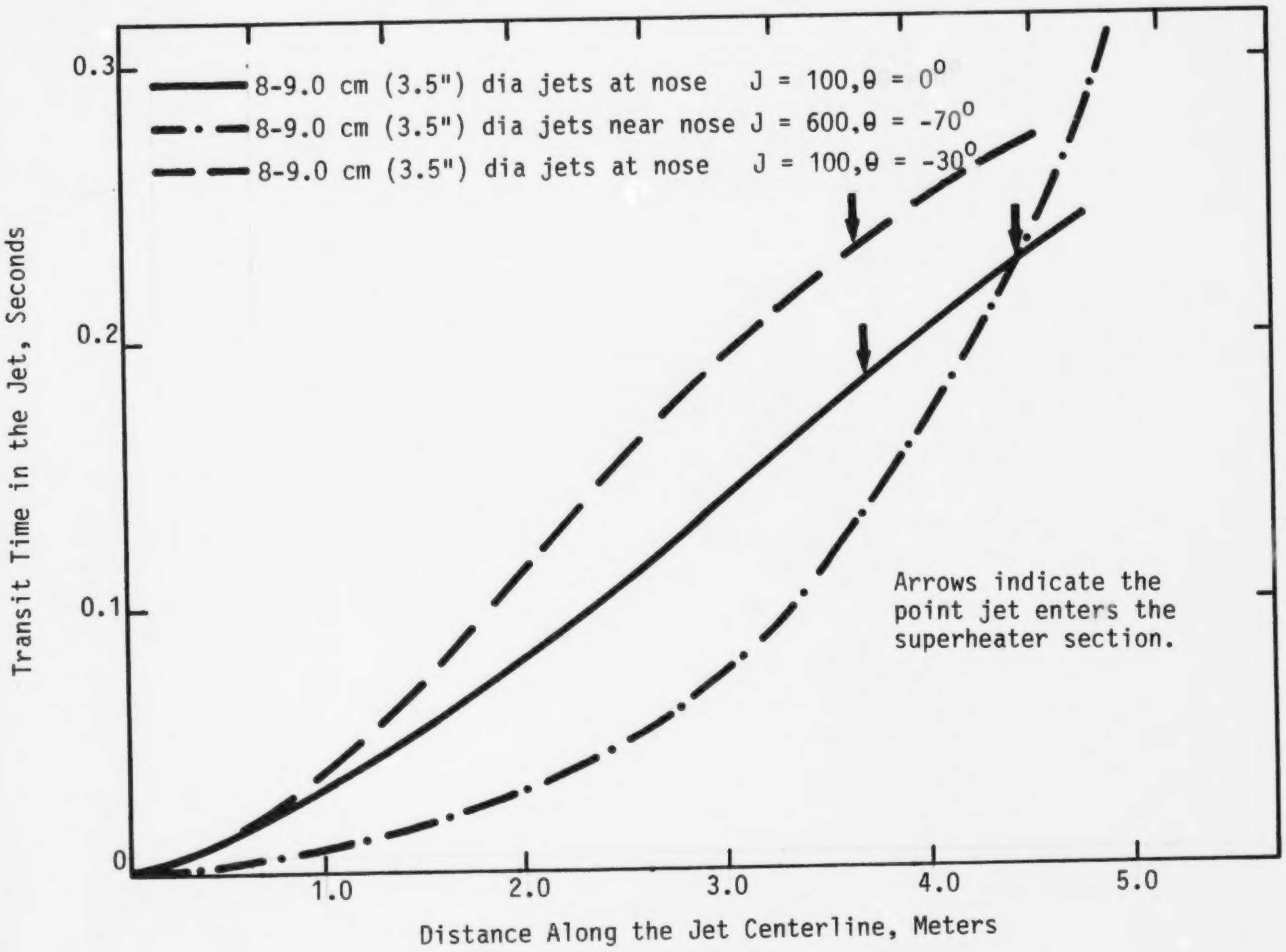


Figure 8-23. Residence times in the horizontal and angled jets.

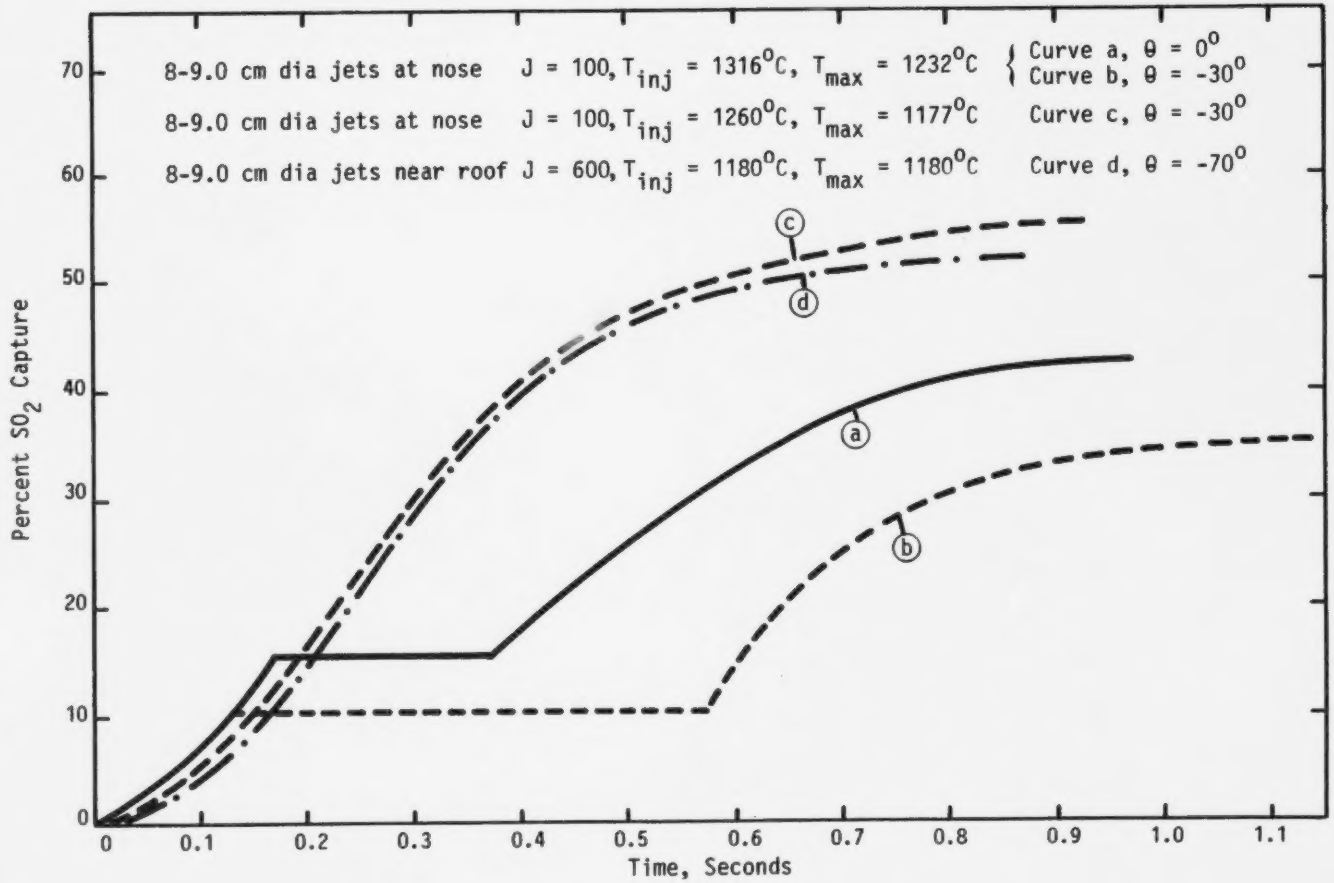


Figure 8-24. Sulfur capture predictions for the angled and horizontal jet systems.

tilting the jets downward is to increase the residence time in the unfavorable temperature zone where sulfation is not favored based on the thermodynamic equilibrium constraint. This results in lower sulfur capture because of the sintering of the sorbent at these high temperatures and lack of sulfation. However, if the jets are moved to a higher elevation where the temperature at the injection location is about 1260°C, then the increased residence time due to tilting of the jets can be used to advantage, resulting in considerably higher sulfur captures as given by curve (c) in Figure 8-24. The benefit of highly angled jet injection is of the same order as the moderately tilted jets injected at the same temperature as indicated by curve (d) in Figure 8-24.

The above prediction for the downward-angled jet showed that injection at 1316°C (2400°F) caused the sorbent to be heated to a temperature too high for sulfation. An additional calculation was made for the angled-jet case with injection at 1260°C (2300°F). Thus, the time spent by the sorbent in the sulfation window was reduced, but this also reduced the peak temperature seen by the jet to 1173°C (2144°F), and allowed sulfation to proceed for the entire residence time. The sulfur capture increased from 43 percent to 56 percent (or 49 percent if incomplete dispersion was taken into account). This can be compared with the 43 percent predicted for the case where the jets were injected horizontally into 1316°C (2400°F). This indicates the benefit of controlling peak sorbent temperature to avoid over-heating, and suggests that the injectors should be located at a point which would give peak sorbent temperature of about 1177°C (2150°F). For the injection case considered here (8 jets at a single level), the appropriate injection temperature would be 1260°C (2300°F). If the injectors were located at this level, there appears to be benefit in angling the injectors downward to increase the sorbent residence time at the optimum temperatures.

8.4 Summary of Results

Table 8-3 summarizes the predictions that were made for sulfur capture at the EPA's LIMB demonstration boiler (Edgewater). Predictions based on three methods are listed. Method 1 was the empirical interpretation scheme

TABLE 8-3. SUMMARY OF SULFUR CAPTURE PREDICTIONS

	Capture at Ca/S = 2.0		
Case	Method 1	Method 2	Method 3
I - 22 jets - 2 level	Linwood 45% Marblehead 39%	--	--
II - 8 jets - 1 level	--	Linwood 41%	Linwood 43%
III - 8 jets - 1 level at -30^o	--	--	Linwood 38%
VI - 8 jets - 1 level at -30^o T_{inj} 2300	--	--	Linwood 49%

outlined in Section 8.3.1 utilizing isothermal modeling and bench scale desulfurization data. Method 2 involved pilot scale experiments conducted under boiler-like conditions discussed in Section 8.3.2. Method 3 predictions were made with the jet and the sulfur capture models.

The predicted sulfur capture for the B&W preferred twenty-two jet cases was 45 percent for Linwood atmospheric hydrate based on isothermal modeling and CTT experimental data. For the originally selected case of eight jets injected opposite the nose, the prediction of Linwood based on pilot scale test results gave 41 percent capture, compared with 43 percent based on the modeling approach. These predictions are surprisingly close, giving some confidence to the estimate.

Although the modeling approach provides estimates that should be viewed cautiously with regard to absolute levels of capture, it accounts functionally for the major influences of jet parameters on mixing, temperature and concentration history, and their effects on the sulfur capture process. Thus, it provides a means of estimating the effects of changes of injection conditions. Cases 2, 3, and 4 in Table 8-3 illustrate some of these effects. Angling the jets downward provides a useful increase in sorbent residence time, but if injection is at 1316°C (2400°F), the sorbent will get too hot and capture will be reduced below that for the horizontal jets.

Shifting the jets further downstream so that they are injected at 1260°C (2300°F) overcomes this sorbent overheating and produces an increase in capture even though the residence time is reduced.

9.0 SUMMARY OF RESULTS

A series of experimental and theoretical studies were conducted to investigate the mixing problem of a row of sorbent jets injected into a stream of hot combustion products in the upper furnaces of the wall-fired boilers. The main objective of these studies was to develop a sorbent injection system design methodology for wall-fired boilers. The four investigations undertaken in this research program involved:

- Isothermal modeling studies of jet injection in boiler type flow fields.
- Computational modeling studies of jet injection into a cross flow stream with its extension to non-uniform, non-isothermal boiler flows.
- Pilot scale combustion tests to determine the effects of key jet injection parameters on sulfur capture.
- Large scale combustion tests to determine the influence of same injection parameters at a larger scale for scale-up implications.

The key results from these studies are summarized in the following:

- Isothermal tests and jet models identified that the key injection parameters influencing the mixing are jet size, jet velocity, and the number of jets. While jet size and velocity both affect the entrainment and penetration characteristics, the number of jets has an influence on the overall coverage of the furnace flow with sorbent.
- The pilot scale combustion tests designed to study the influence of these injection parameters on sulfur capture showed that injection velocity had virtually no effect on sulfur capture. However,

sulfur capture levels dropped as the dispersion became poor through reduction of the number of jets.

- Sorbent injection tests at a larger scale in a simulation of a small utility boiler furnace showed a rather strong dependence of sulfur capture on the jet momentum which was contrary to the results from the smaller scale. However, these results were determined to be the consequence of the unique flow field in this particular furnace.

- Two approaches formulated to interpret the effect of dispersion on sulfur capture, one using isothermal modeling and the other computational jet modeling, gave encouraging agreement between the measurements and predictions.

Based on these results a methodology, consisting of empirical, computational and experimental tools, was established. Specifically, the methodology involves:

- As a first step, empirical formulas and a simple procedure can be utilized to determine the number, the size and the velocity of injection jets to achieve good mixing with the furnace flow. The mechanics of this process was described in Section 7.0. It requires, as input, the structural and operational characteristic of the boiler under study.

- As a second step, isothermal modeling tests can be used to optimize the preliminary injection system designs based on the empirical schemes. This approach also provides a simple scheme to predict the sulfur capture potential from a particular injection scheme

- As a third step, computational models of jet injection process developed here can be used to replace some of the steps in the empirical approach. The jet mixing model can also be coupled with the existing calcination/sulfation models to predict the progress of sulfation with time in the sorbent jets. However, caution should be exercised in utilizing this approach to predict sulfur capture levels since there are uncertainties and knowledge gaps in the physics and chemistry of calcination and sulfation process.

The latter two methods were applied to several sorbent injection schemes for the Edgewater boiler in Section 8.0 of this report. The sulfur capture predictions from both methods were in good agreement.

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APPENDIX A. QUALITY ASSURANCE AND QUALITY CONTROL ACTIVITIES

A.0 QUALITY ASSURANCE AND QUALITY CONTROL PROCEDURES

Experiments described in this report were conducted under the guidelines and procedures outlined in the Quality Assurance Project Plan, Revision 2, submitted on 3/29/85 and approved by EPA. In the following subsections, the QA/QC activities are documented for three series of tests. Section A.1 concerns the QA/QC activities for the isothermal flow modeling tests. Section A.2 documents the QA/QC checks for the pilot scale combustion tests in the reburning tower furnace. The LWS test QA/QC activities are discussed in Section A.3.

A.1 Isothermal Flow Modeling

Most of the experiments in the isothermal flow models involved flow visualization by visible tracers and the recordings of flow patterns on photographic plates. These tests were of qualitative nature and did not require any QA/QC checks. The two key types of experiments requiring QA/QC were:

- CH_4 gas tracer measurements
- Velocity measurements

Figure A-1 shows the tracer injection and measurement systems. During the tests, the infrared CH_4 detector (Beckman NDIR 864) was calibrated before and after each test run by a zero gas (nitrogen) and a span gas (CH_4, 995 ppm). In addition, the calculated and measured CH_4 tracer concentrations in the exhaust of the flow model (well-mixed concentration of tracer in the air stream) were compared to determine any major leaks in and out of the test models. Measured flow rates of methane and air supply to the model were used to calculate the well-mixed tracer concentration. These values were compared with the tracer concentration measured in the exhaust duct where it was believed that the tracer was totally dispersed in the air flow. Table A-1 shows the relative deviation of the measured and calculated tracer concentrations. For all the cases presented in the table, the deviation was less than 15 percent with the exception of two test cases.

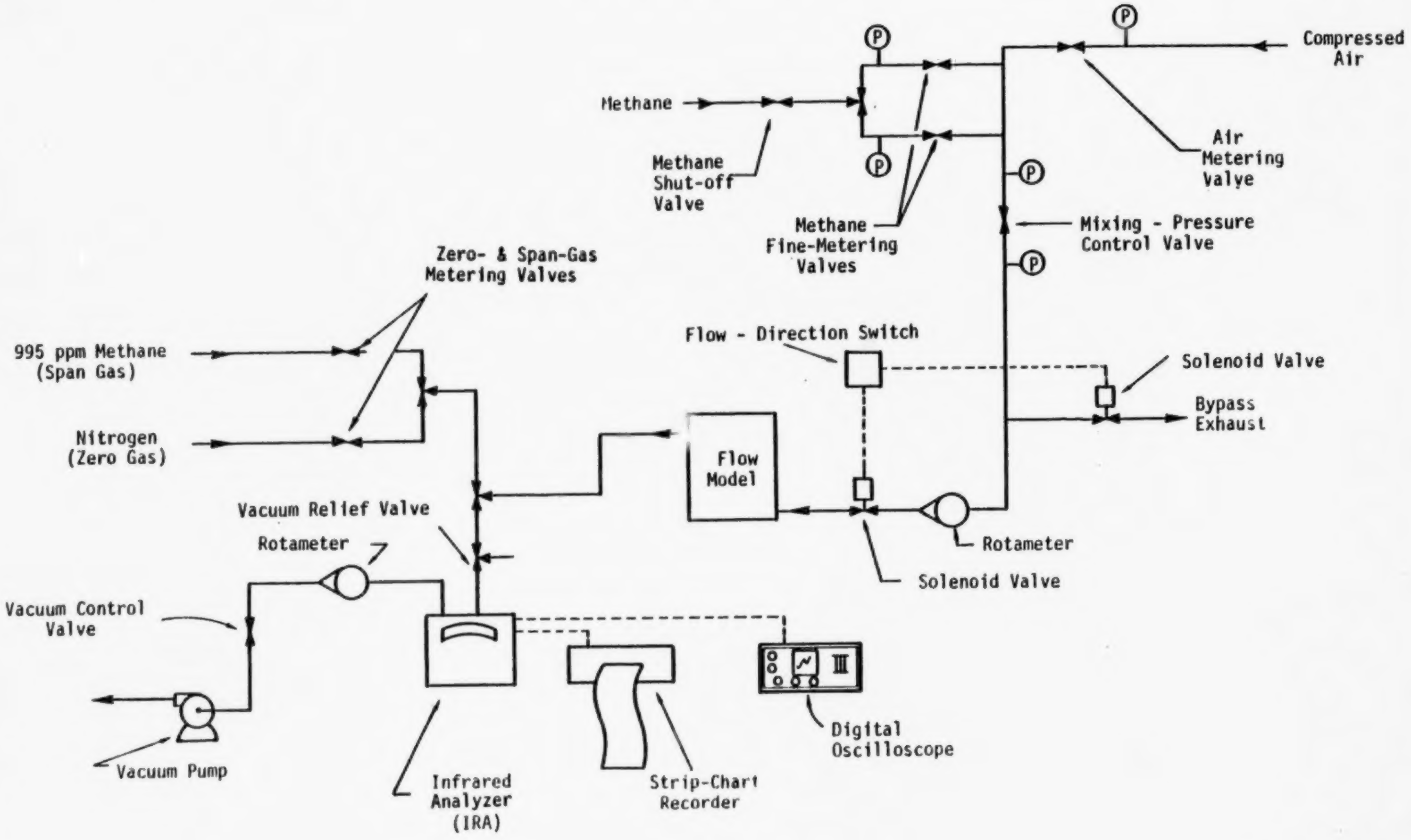
Compressed Air
Methane
Methane Shut-off Valve
Methane Fine-Metering Valves
Air Metering Valve
Mixing - Pressure Control Valve
Zero- & Span-Gas Metering Valves
995 ppm Methane (Span Gas)
Nitrogen (Zero Gas)
Flow - Direction Switch
Solenoid Valve
Bypass Exhaust
Flow Model
Rotameter
Solenoid Valve
Vacuum Relief Valve
Rotameter
Vacuum Control Valve
Vacuum Pump
Infrared Analyzer (IRA)
Strip-Chart Recorder
Digital Oscilloscope

Figure A-1. Methane injection-measurement system.

TABLE A-1. QA/QC FOR DISPERSION MEASUREMENTS

No. of Jets	Jet Dia. cm.	Injection Location	J	C_{calc}(ppm)	C_{mea}(ppm)	Percent* Deviation %
2	1.27	Nose	250	729	810	10.0
2	1.27	Nose	150	791	730	8.4
2	1.27	Nose	100	558	533	4.7
2	1.27	Nose	50	421	540	22.0
2	1.27	Above Nose	150	678	685	1.0
2	1.27	Under Nose	150	418	633	33.9
2	1.27	Under Nose	100	441	428	3.0
2	1.27	Under Nose	50	462	463	0.2
1	1.27	Nose	150	733	680	7.8
1	1.27	Nose	100	556	563	1.2
1	1.27	Nose	50	557	552	0.9
3	1.27	Nose	150	496	533	6.9
1	2.54	Nose	150	432	405	6.6
1	2.54	Nose	100	630	648	2.8
1	2.54	Nose	50	438	515	14.9
1	2.54	Under Nose	150	719	820	12.3
3	0.84	Nose	150	378	410	7.8
3	0.84	Under Nose	150	504	483	4.3

(*) Percent Deviation = $$\frac{|C_{mea} - C_{calc}|}{C_{mea}} \times 100$$

Velocity measurements were conducted with a single hot-wire anemometer calibrated with a special calibration device. The calibration device manufactured by TSI Inc. is shown in Figure A-2. It includes a nozzle with a calibrated orifice meter to determine the flow rate. The hot wire probe is positioned at the potential core of the jet issuing from an orifice. The pressure drop versus velocity calibration curve supplied with the calibrator is used to determine the velocity versus signal for the hot wire anemometer. The calibration curve generated during the experiments is shown in Figure A-3. The calibrations generated in the calibrator were checked against the other calibrations conducted in the potential cores of 1.27 cm and 2.54 cm diameter jets. The agreement between the three different sets of calibrations was within a few percent of the average.

A.2 Tower Furnace Combustion Tests

This subsection concerns the QA/QC activities conducted during the combustion tests in the tower furnace experiments. Results are presented for the critical measurements only. Critical measurements are those which directly affected the results and conclusions in this report. The critical measurements were:

- Fuel flow rates
- Sorbent flow rates
- Combustion (sorbent carrier) air flow rates
- Furnace gas temperatures
- Furnace exhaust gas composition
- Solid compositions

Table A-2 summarizes the precision, accuracy and completeness for these critical measurements. The values for precision are defined as the relative standard deviation (ratio of the standard deviation to the mean of replicate measurements expressed as percentage). Accuracy is the percent difference between the measured value and a known or standard value. Completeness is the percentage of valid data obtained compared to the total amount of data planned to be obtained. The QA goals for the most critical measurements were

Gas Probe Calibrator - Model 1125

• Calibrate most probes from 0.1 ft/sec to MACH #1 • Easy to use • Can be used with most gases

The Model 1125 Calibrator is designed to calibrate hot wire and hot film anemometer probes over a wide velocity range. Reference calibration data is furnished giving velocity vs. pressure drop for each range in air. Useful accessories include Models 1156-1, 1151-1 probe supports.

Also included with the Model 1125 Calibrator is the Model 1125R-1 Probe Rotator. The probe rotator provides a rigid mounting for calibrating probes on the exterior nozzle and allows angular calibrations to be performed on most probes.

Calibrator Specifications

Velocity Range: Probes can be calibrated from 0.1 ft/sec. to MACH #1 (3 cm/sec to M #1) by appropriate use of interior chamber, interior nozzle and exterior nozzle.

Free Stream Velocity Accuracy: ±2% above 10 fps; ±5% 0.5 to 10 fps; ±10% below 0.5 fps (Accuracy traceable to Laser Velocimetry).

Background Turbulence Intensity: 0.2% at 33 mps (100 fps)

Nozzle Sizes: 72 mm (2.83 in.) Dia. Interior Chamber; 6.5 mm (0.65 in.) Dia. Interior Nozzle; 3.8 mm (0.15 in.) Dia. Exterior Nozzle

Temperature Limits: 0 - 65° C (32 - 150° F)

Pressure Limit: 7 ATM Internal (20 ATM Max. into Regulator)

Power Required: 115V AC 60 Hz or 230V AC 50 cps (switch selectable)

Size: 608 mm High x 457 mm Wide x 254 mm Deep (20" High x 18" Wide x 10" Deep)

Weight: 7 kg (15 lbs.)

Required Air Supply: 100 psi at maximum velocity

PROBE ROTATOR SPECIFICATIONS:

Rotational Scale: 0 - 360°, 2° graduation with .2° vernier

Rotational Accuracy: ±0.5°

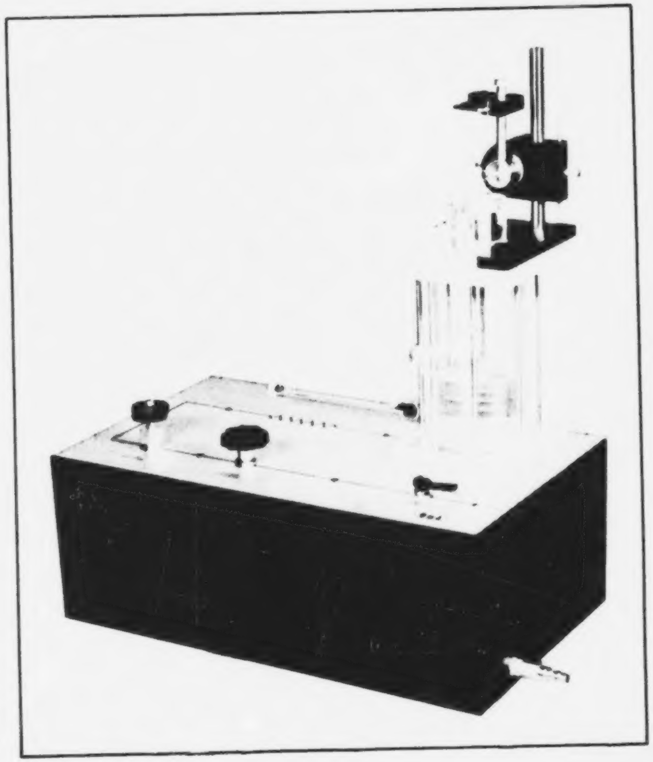

Figure A-2. TSI Hot Wire Calibration Rig. © Copyrighted by TSI, Inc. Reproduced with Permission.

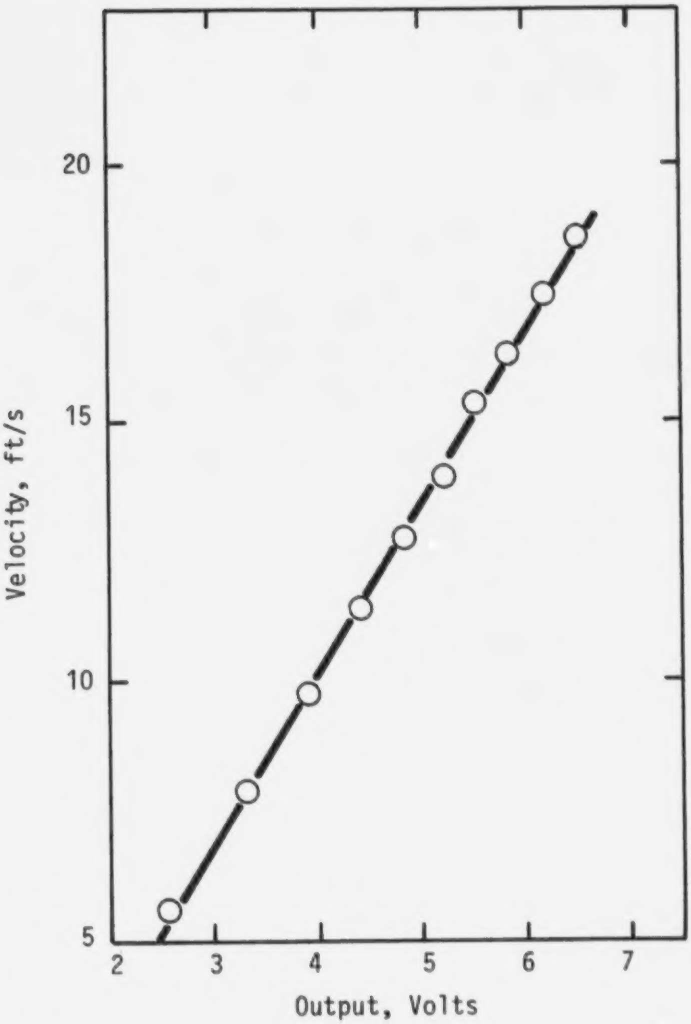

Figure A-3. Calibration curve generated for 1220-20 Hot Wire Probe (TSI).

TABLE A-2. PROGRAM OBJECTIVES FOR MEASUREMENT PRECISION ACCURACY AND COMPLETENESS

Parameter	Measurement Method	Precision: % Rel. Standard Deviation		Accuracy, %		Completeness, %	
		Actual	Goal	Actual	Goal	Actual	Goal
Fuel Flow Rate							
Coal	Volumetric Feeder	-	5	-	5	100	100
Gas	Rotameter						
Sorbent Flow Rate	Volumetric Feeder	-	5	-	5	90	90
Combustion/Sorbent Carrier Air Flow Rates	Venturi Flowmeter/ Orifice Flowmeter	≤4.8	5	-	5	100	100
Combustion Air Preheat Temp.	Thermocouples	2.5	5	2.5	5	90	90
Gas Species	Continuous Monitors	-	2		20	>90	90
NO/NO$_x$	Chemiluminescence			9.9			
CO	NDIR			-			
CO$_2$	NDIR			2.9			
SO$_2$				6.0			
O$_2$	Paramagnetic			19.2			
Furnace Gas Temperature	Suction Pyrometer	2.5	5	2.5	5	90	90
Solids Comp.			5		5	>90	90
Carbon Hydrogen Nitrogen	Perkin Elmer 240B						
Moisture	ASTM						
Ash	ASTM						
Sulfur	Leco SC32						
Heating Value	ASTM						
Sorbent Surface Area	BET Analysis		5	-	5	90	90
Solids Concentration	Laser Extinction		10		10	90	90
Sorbent Composition						90	90
Carbon	Perkin Elmer 240B		2		2		
Sulfur	Leco SC32		10		10		
Ca	EDTA Titration		2		10		

met during these tests. In the following sections, each measurement is described and the various QA checks are discussed.

A.2.1 Fuel Flow Rates

Fuel flow rates were monitored continuously during the tests with calibrated instruments. The coal and natural gas flow rates were monitored with the following instruments:

a) Coal flowrate with volumetric twin-screw-type feeder
b) Natural gas flowrate with factory calibrated rotameter.

The coal feeder was calibrated by operating the feeder system at constant feed rate and determining the mass of coal collected in a measured time period. A calibration graph showing the mass flux of coal as a function of feeder speed setting was produced as shown in Figure A-4. Pre-ground and dried coal was supplied to the feeder from coal bins.

As an independent check on the fuel flow rates, the fuel composition, the composition of combustion products in the exhaust and the measured air flow rates were used to calculate the thermal heat input into the furnace. This heat input is called actual load of the combustion system. This was routinely compared with the calculated heat input based on fuel heating value and mass flow rate of natural gas or Pittsburgh #8 coal. Before switching from natural gas to coal-firing, the actual load and theoretical load were checked to agree within 5 percent of each other. No sulfur capture data were taken unless those two loads were within 10 percent. In order to check the proper operation of the experimental systems and identify any problems before the testing commenced, the following checks were performed in the beginning of every test day:

a) Furnace leak check
b) Gas sampling system leak check
c) Combustion air measurement system check
d) Fuel flow rate measurement check

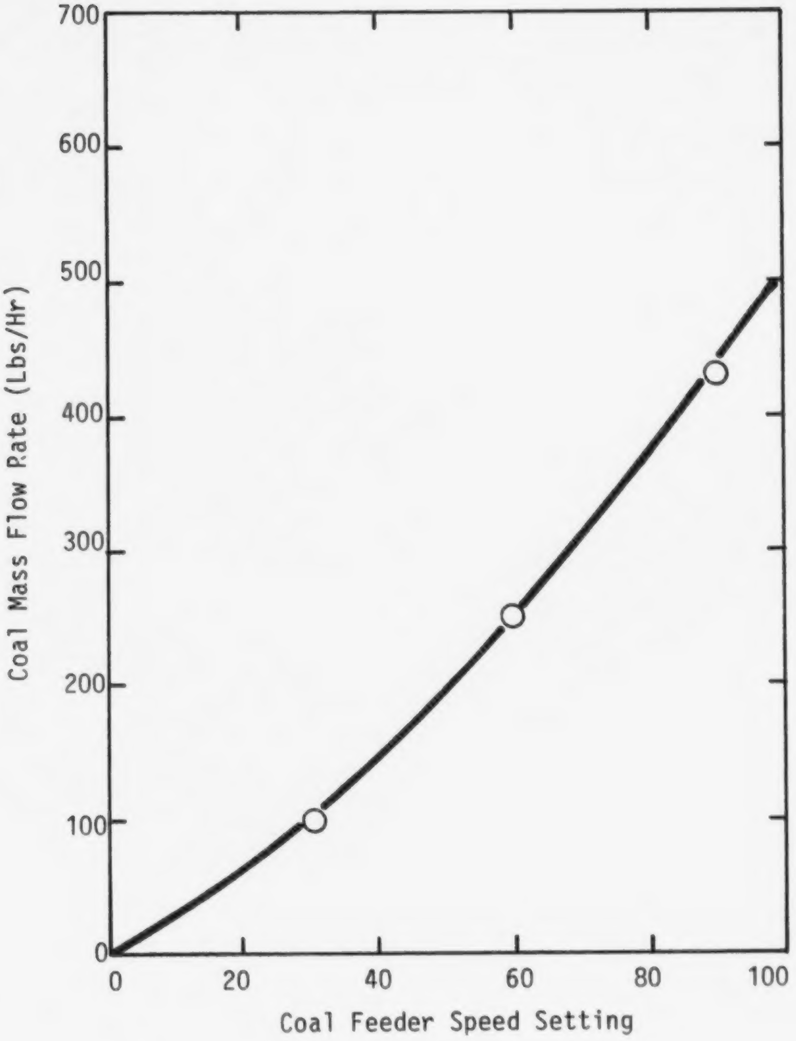

Figure A-4. Pittsburgh #8 coal mass flow rates vs. coal feeder speed setting.

A.2.2 Sorbent Flow Rates

Sorbent flowrates were measured by a screw-type volumetric feeder similar to that used for the coal flowrate measurement. The feeder was calibrated as described for coal feeder and is shown in Figure A-5.

A.2.3 Combustion (Sorbent Carrier) Air Flowrates

The preheated combustion air flow rates to various burner passages were measured with calibrated venturi flow meters. The flowmeters were routinely calibrated before each test series by pitot tube measurements and calculations. The pitot-tube calibrations yielded a constant for each venturi flowmeter. Applying this constant, the air flowrates were determined from the measured pressure drop in each venturi and the air temperature in accordance with:

$$\dot{M} = K(\Delta P/T)^{1/2}$$

where:

$\dot{M}$ = mass flow rate of air, SCFM
P = the venturi pressure drop, inches of H_2O
T = the absolute temperature, ^{o}R
K = the dimensional venturi constant.

The calibration constants, K for these series of tests are given in Table A-3 along with three previous calibrations. The average relative standard deviation for the three venturi flow meters was 3.43 percent. The pressure drops across the elements were sensed by pressure transducers and input to a continuous data reduction system.

The sorbent carrier air flow rates were measured with calibrated 3/4" orifice flowmeter. Several calibration curves are shown in Figure A-6 along with the calculation formula.

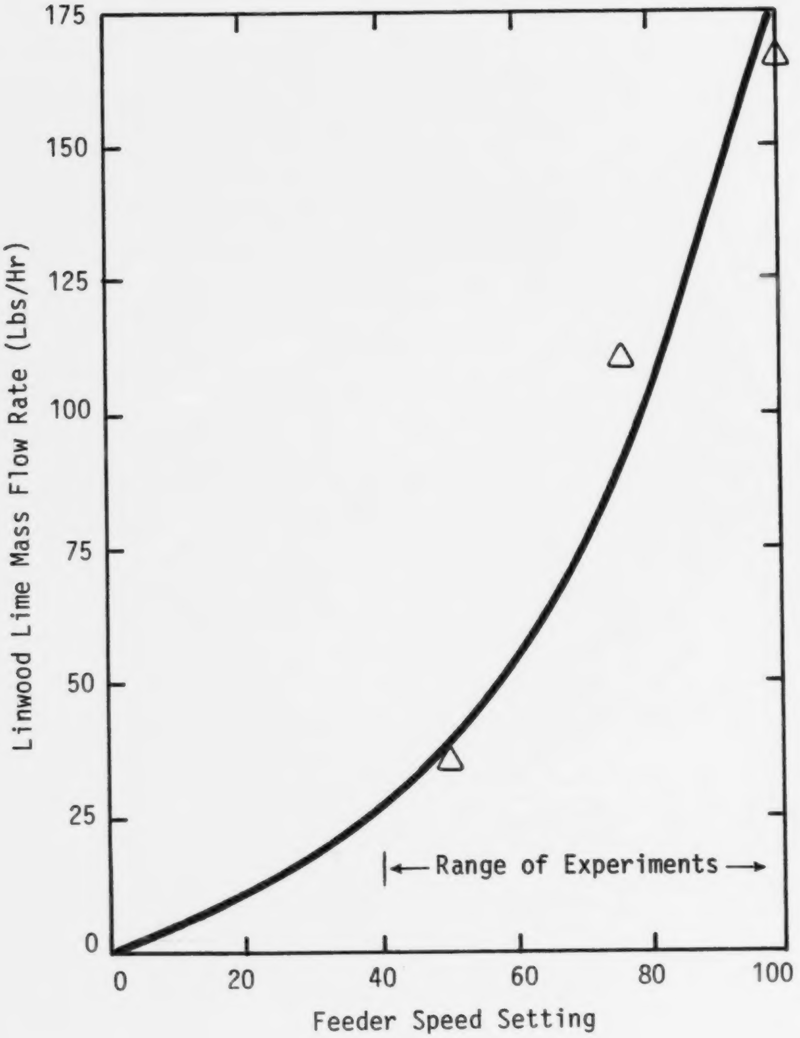

Figure A-5. Linwood atmospheric hydrated lime mass flow rates vs. feeder speed setting.

TABLE A-3. TOWER FURNACE VENTURI FLOWMETER CALIBRATIONS

Calibration Date	* Venturi Calibration Constant, K		
	Venturi #1	Venturi #2	Venturi #5
10/31/83	5626	8778	8427
01/07/84	5044	8448	7826
10/01/84	5218	8448	7826
10/17/85	4993	8330	7697
Average	5220	8501	7944
Standard Dev.	299.	167	284
Rel. St. Dev., %	4.77	1.96	3.57

$$* \quad \dot{M} = K \sqrt{\frac{\Delta P}{T}}$$

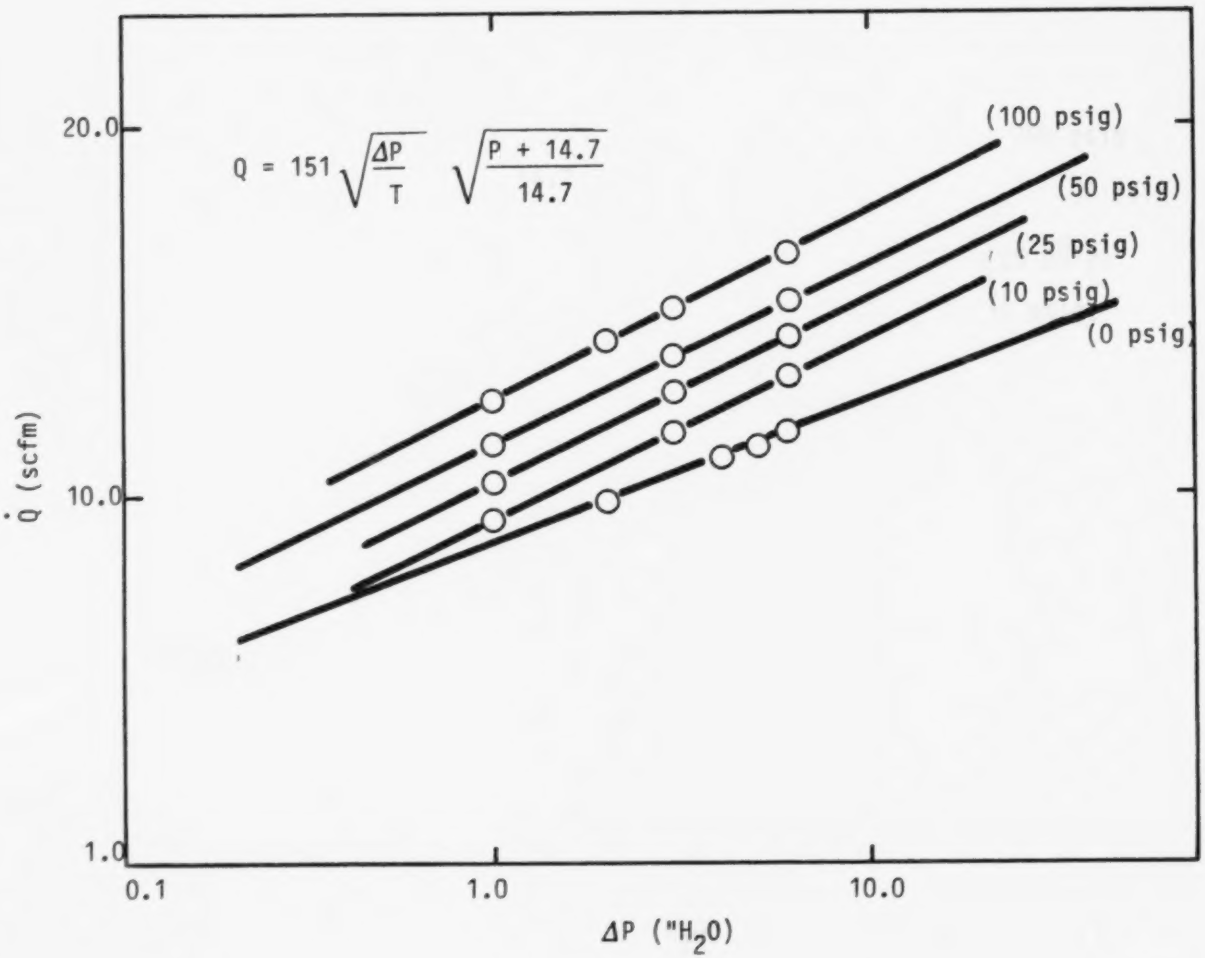

Figure A-6. Calibration curves of 3/4" orifice flow meter.

A.2.4 Furnace Gas Temperatures

Gas temperatures at the nose level of the reburning tower and before and after the cooling coils were measured with single shield suction pyrometers. Figure A-7 shows the construction of the suction pyrometer. Typically, S-type thermocouples were used in these pyrometers. These thermocouples were manufactured according to the ASTM standards. The entire measurement system is shown in Figure A-8. The pyrometer was placed in the flue gas stream with the opening in the outer ceramic sheath pointing downstream. A sufficient gas sample was drawn around the thermocouple tip such that the convective heat transfer for the gas to the thermocouple dominated over the radiation heat loss from the thermocouple tip to the surroundings. Regular K-type thermocouples were used to measure temperatures at the location of gas sampling. The error limits for K-type thermocouple are ± 2.2°C or ± 0.75 percent of the reading (whichever is greater). The error limits for S-type thermocouple are ± 1.5°C or 2.5 percent of the measured temperature (whichever is greater). These pyrometers were calibrated to determine the optimum suction gas flow rate for temperature measurements. The calibration curve is shown in Figure A-9. During temperature measurements, the suction flow rates were monitored by an orifice meter in the suction stream. In all tests, the suction flowrate was such that the pressure drop across the orifice flow meter was kept above 0.2 inches of H_2O.

A.2.5 Furnace Exhaust Gas Compositions

Concentrations of NO_x, CO, CO_2, O_2 and SO_2 were measured at the entrance of the SWS furnace after the cooling coils of the tower. The temperature at the sample port was continuously monitored and was about 1500°F. Because the active sorbent particles present in the sample stream during the testing, a stainless steel phase discrimination probe, shown in Figure A-10 was utilized to minimize the contact of solid particulate material with the gas sample. The probe was positioned at the center of the duct, and supplied two gas streams simultaneously: the main, particle-laden stream which was used for continuous monitoring of O_2, CO, CO_2, NO_x and the side, nearly particle-free, stream which was used for SO_2 measurements. Sample conditioning for the two

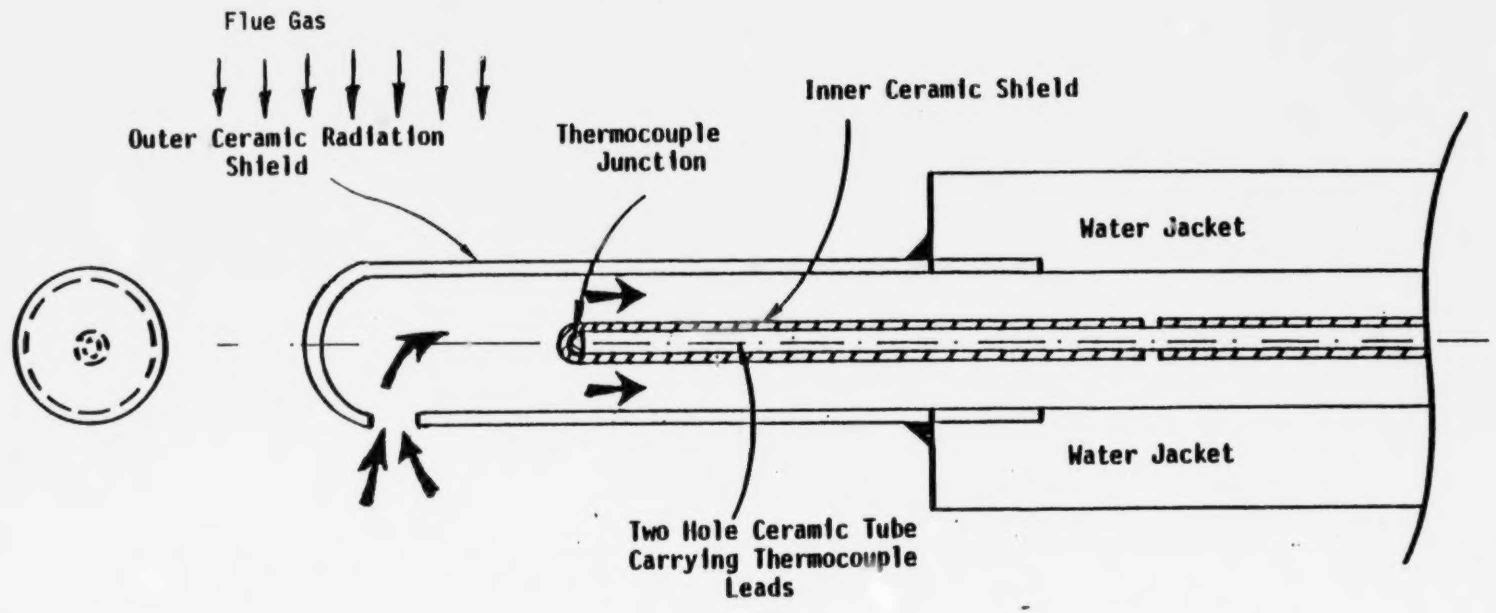
Flue Gas
Outer Ceramic Radiation Shield
Thermocouple Junction
Inner Ceramic Shield
Water Jacket
Water Jacket
Two Hole Ceramic Tube Carrying Thermocouple Leads

Figure A-7. Suction pyrometer tip construction.

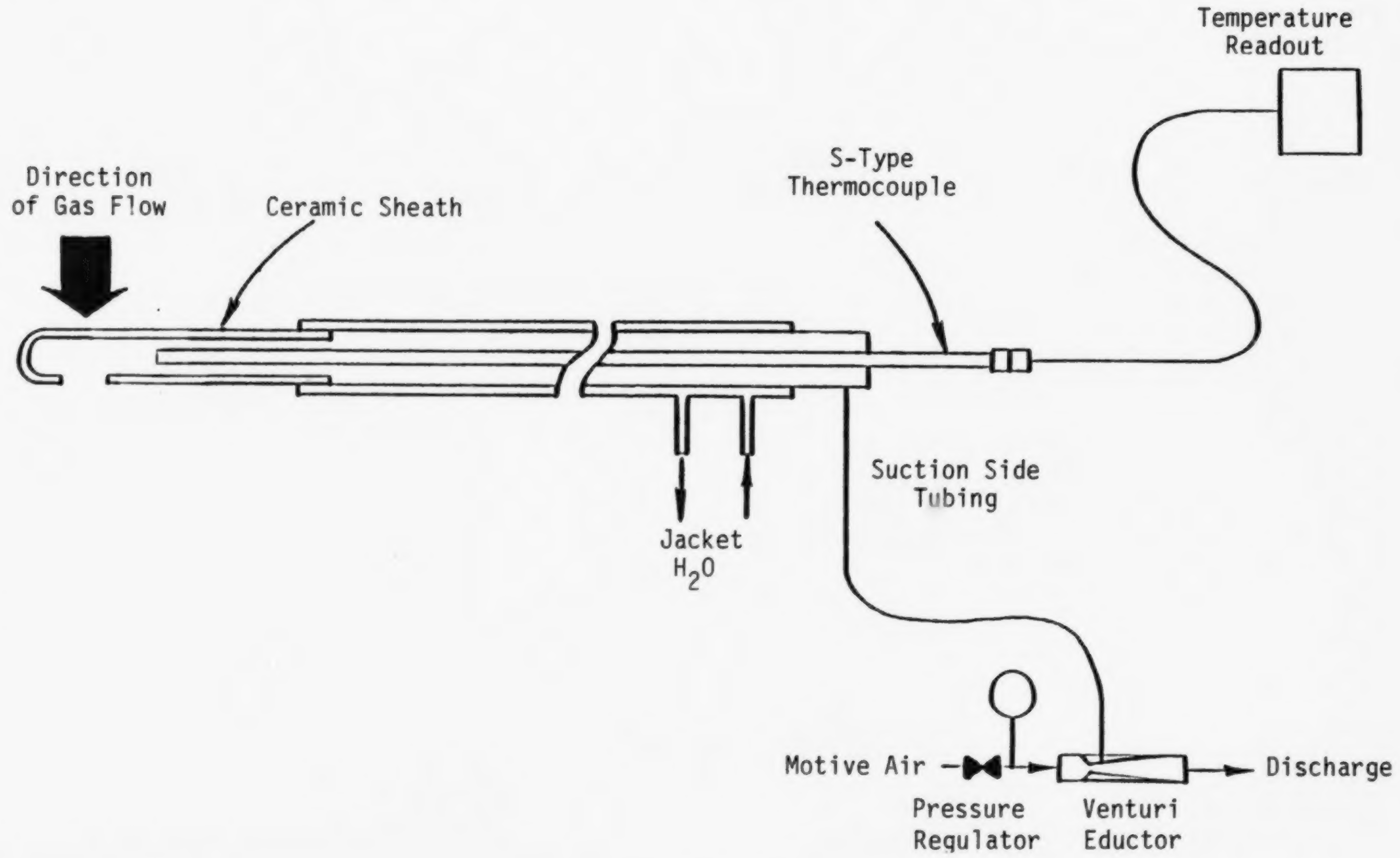
Direction
of Gas Flow
Ceramic Sheath
S-Type
Thermocouple
Temperature
Readout
Suction Side
Tubing
Jacket
H_2O
Motive Air
Pressure
Regulator
Venturi
Eductor
Discharge

Figure A-8. Gas temperature measurement system.

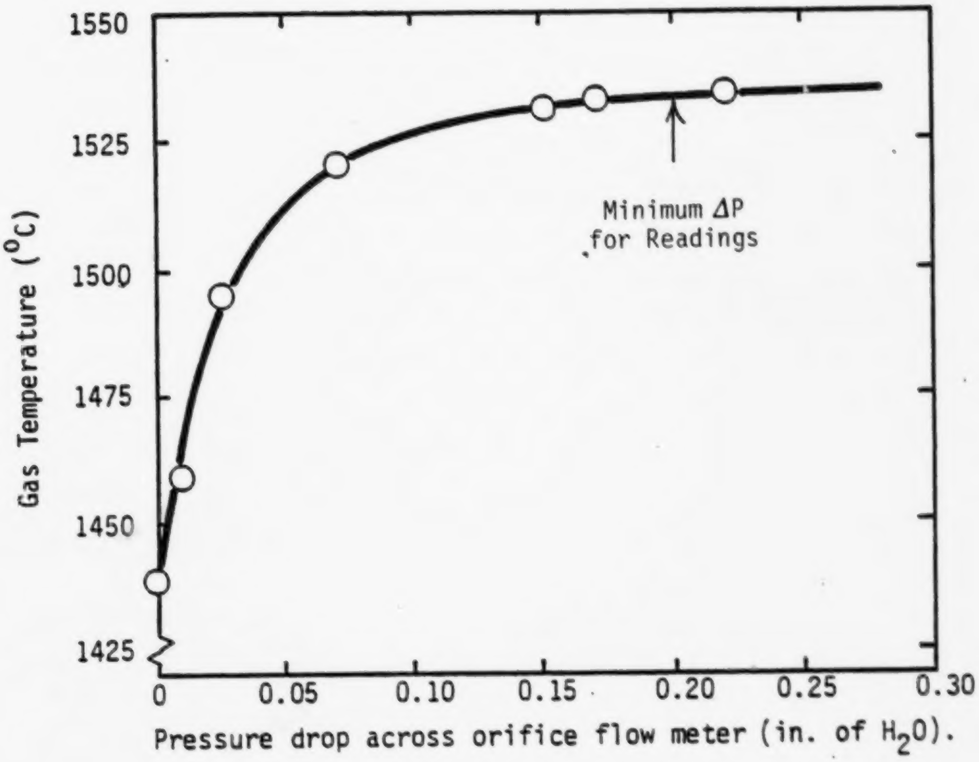

Figure A-9. Suction flowrate calibration for suction pyrometer.

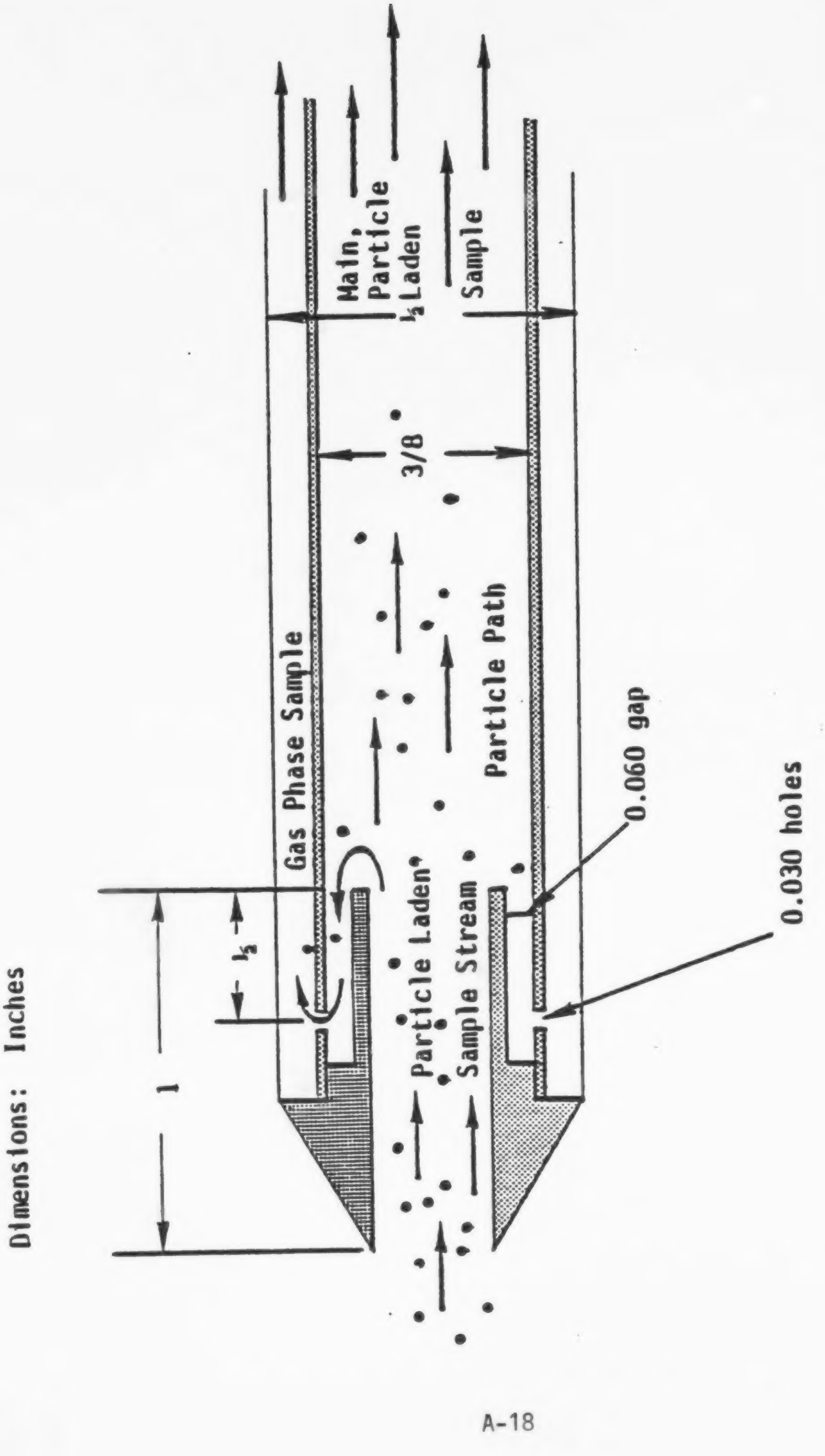
Dimensions: Inches
1
½
Gas Phase Sample
Particle Laden
Sample Stream
Particle Path
3/8
Main, Particle Laden
½
Sample
0.060 gap
0.030 holes

Figure A-10. Phase discrimination probe.

streams was somewhat different as shown in Figure A-11. The main sample (O_2, CO, CO_2, NO_x) stream was dried using an iced condenser, filtered, pressurized, and delivered to the continuous monitor instrumentation. The SO_2 gas sample was transported in a heated Teflon line maintained above 115°C under vacuum to a heated filter followed by a permeation tube drier. The permeation tube drier selectively removed water vapor from the gas sample. Dry air was used as the drying medium in the permeation drier. The sample was then pressurized and delivered to the analytic system of the SWS furnace (see Figure A-12). Every morning before testing, a leak check on the sample system was performed by plugging the probe and checking the indicator on the sample rotameter. If the indicator did not drop to zero, then a leak in the system was present and required fixing.

Table A-4 lists the specific instruments used for continuously monitoring gas species compositions. To insure accuracy, the instruments were operated according to EPA Performance Standards 2 and 3. Each instrument was calibrated by two gases: a zero gas and a span gas at approximately 90 percent of span. Most instrument calibrations were performed in two to three hour intervals during testing. The DuPont SO_2 analyzer was calibrated right before and after sorbent injections. The standard calibration gases were certified standard grade mixtures, compared by the manufacturer to primary standard gas mixtures (NBS traceable, gravimetrically prepared).

A series of quality assurance checks were carried out before this series of tests commenced. Instrument performance tests were conducted to determine the relative accuracy, calibration error and (2-3)-hour drift. Instrument calibrations were performed about every 2-3 hours during testing in addition to the calibrations performed at the beginning and the end of each test day. Table A-5 summarizes these results. The relative accuracy was determined by comparing the instrument values to values obtained using EPA Reference Methods. There is currently no performance specification for the CO monitor or standard reference method for CO determination, but calibration error and (2-3)-hour drift tests were conducted according to the guidelines for the

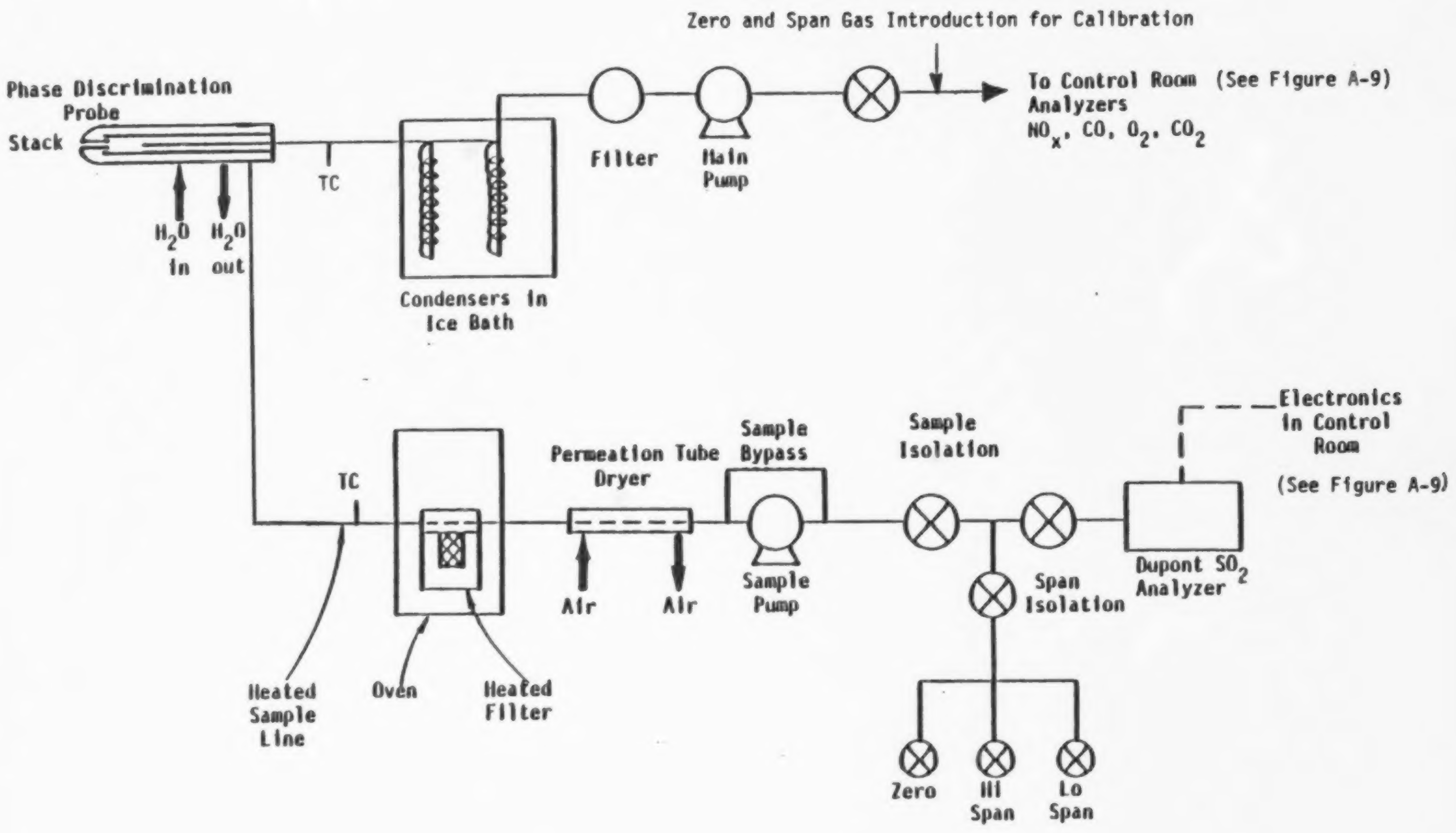
Zero and Span Gas Introduction for Calibration
Phase Discrimination Probe
Stack
H_2O In
H_2O out
TC
Condensers in Ice Bath
Filter
Main Pump
To Control Room (See Figure A-9)
Analyzers
NO_x, CO, O_2, CO_2
TC
Permeation Tube Dryer
Air
Air
Sample Bypass
Sample Pump
Sample Isolation
Span Isolation
Dupont SO_2 Analyzer
Electronics in Control Room
(See Figure A-9)
Heated Sample Line
Oven
Heated Filter
Zero
Hi Span
Lo Span

Figure A-11. Schematic for SWS sampling system.

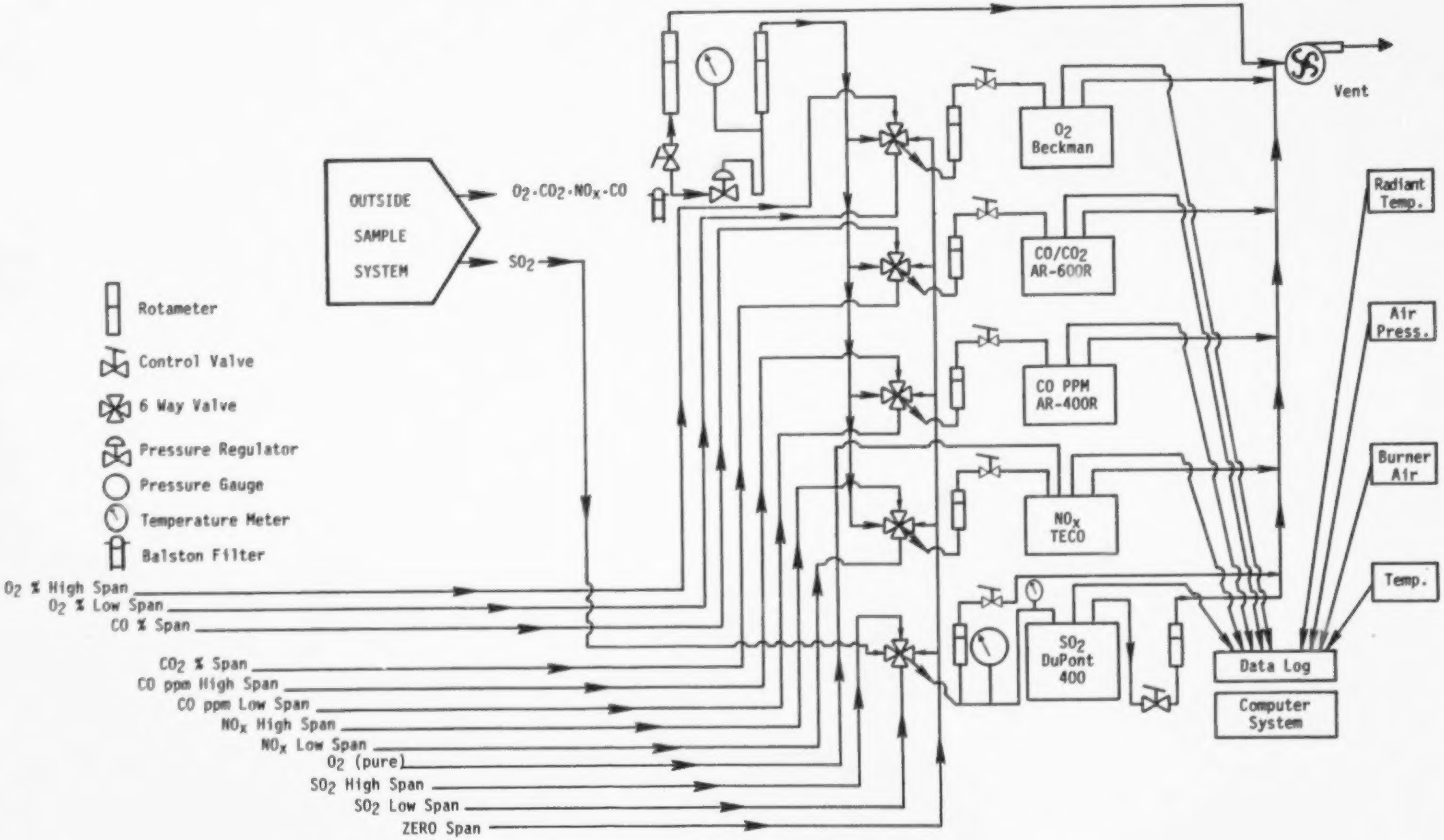
OUTSIDE SAMPLE SYSTEM
$O_2 \cdot CO_2 \cdot NO_x \cdot CO$
SO_2
Rotameter
Control Valve
6 Way Valve
Pressure Regulator
Pressure Gauge
Temperature Meter
Balston Filter
O_2 % High Span
O_2 % Low Span
CO % Span
CO_2 % Span
CO ppm High Span
CO ppm Low Span
NO_x High Span
NO_x Low Span
O_2 (pure)
SO_2 High Span
SO_2 Low Span
ZERO Span
O_2 Beckman
CO/CO_2 AR-600R
CO PPM AR-400R
NO_x TECO
SO_2 DuPont 400
Vent
Radiant Temp.
Air Press.
Burner Air
Temp.
Data Log
Computer System

Figure A-12. Analytical system of SWS.

TABLE A-4. CONTINUOUS GAS ANALYZERS

Gas Measured	Detection Principle	Manufacturer	Model No.	Range
NO, NO_x	Chemiluminescent	Thermo Electron Corp. (TECO)	10 AR	0-1000 ppm
CO	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR500R	0-500 ppm
CO_2	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR500R	0-20 percent
O_2	Paramagnetic	Taylor Servomex	Type OA 272	0-10 percent
SO_2	UV Absorption	DuPont	400	0-4000 ppm

TABLE A-5. INSTRUMENT PERFORMANCE TESTS SUMMARY

Instrument/ Manufacturer	Relative Accuracy		Calibration Error			(2-3) Hour Drift Test			
	%	EPA Spec	Mid	High	EPA Spec	Zero	EPA Spec	Cali-bration	EPA Spec
O_2--Beckman	19.2	≤20	.26	2.32	≤5.0	0.58	0.4	≤0.50	≤0.4
CO_2--Anarad, Inc.	2.9	≤20	.08	0.31	≤5.0	0.48	0.4	≤2.80	≤0.4
SO_2--DuPont	5.99	≤20	4.05	1.47	≤5.0	2.71	2.0	≤3.53	≤2.0
NO/NO_x--TECO	9.88	≤20	1.59	1.89	≤5.0	0.46	2.0	≤1.06	≤2.0
CO--Anarad, Inc.	-	-	2.17	2.46	-	1.99	-	2.94	-

Note: O_2 & CO_2--EPA Method 3 (Orsat)

SO_2--EPA Method 6

NO_x--EPA Method 7

other analyzers. The results showed that O_2, SO_2 and CO_2 were above the EPA specification. The rest fell within the specified tolerance.

A.2.6 Solid Compositions

Three types of solid samples were collected: Pittsburgh #8 coal, sorbent, and ash. Coal and sorbent samples were grab samples from the feed streams. Ash samples were collected by a glass cyclone. A schematic of the ash sampling system is shown in Figure A-13.

Coal and ash samples were analyzed in EER's laboratory for carbon, hydrogen, nitrogen, ash, and moisture using a Perkin Elmer 240B elemental analyzer and for sulfur using a Leco SC32 sulfur analyzer. Heating value was supplied by Hazen Research Inc. EER routinely determines precision and accuracy by analyzing replicate and standard samples. Results are monitored using quality control charts. Audit samples from EPA's Environmental Monitoring and Support Laboratory were sent to Hazen Research on a blind basis. Results of the analysis of 10 samples over the past 3 years have shown only 1 analysis to be over 2 percent accuracy. Two audit samples analyzed in replicate by Hazen showed precision of less than 0.2 percent. Audit results for the coal heating value are shown in Figure A-14. Audit results of EER's analysis for sulfur are shown in Figure A-15. An interlaboratory comparison with Hazen Research to evaluate the precision and accuracy of EER's carbon, hydrogen, nitrogen, and ash analyses are shown in Table A-6. All values are within the QA goals except carbon and nitrogen. These values exceed the goals due to the low levels of the measurements. The overall precision and accuracy were adequate to satisfy the needs of the program.

A.3 Large Watertube Simulator (LWS) Furnace Testing

A series of quality control checks were conducted to ensure the quality of data taken during these tests. The quality assurance activities conducted during these tests were divided into daily routine and system verification checks:

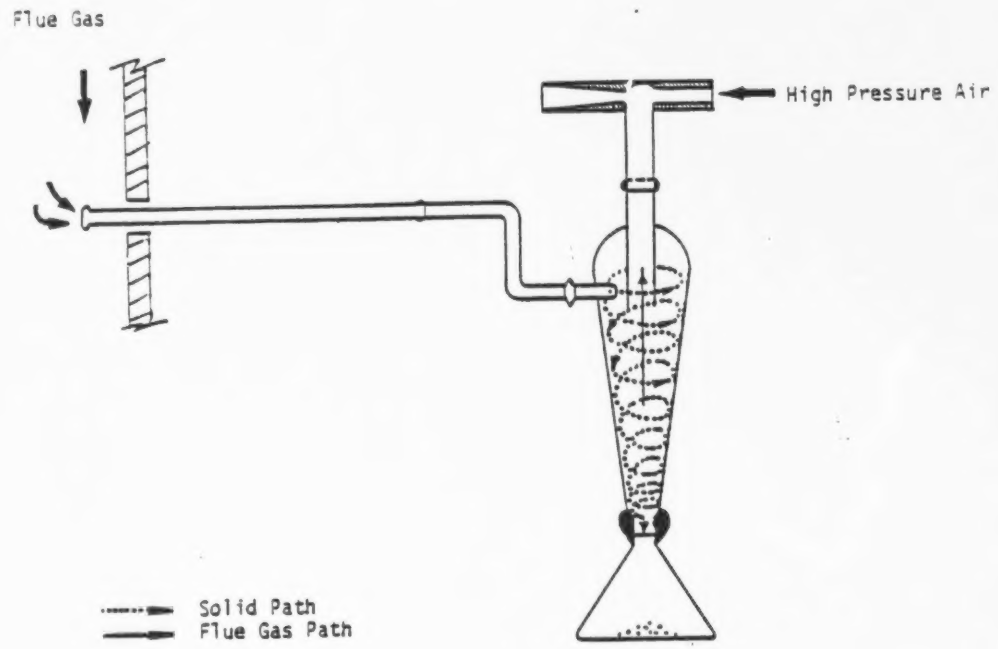
Flue Gas
High Pressure Air
Solid Path
Flue Gas Path

Figure A-13. Ash sampling system.

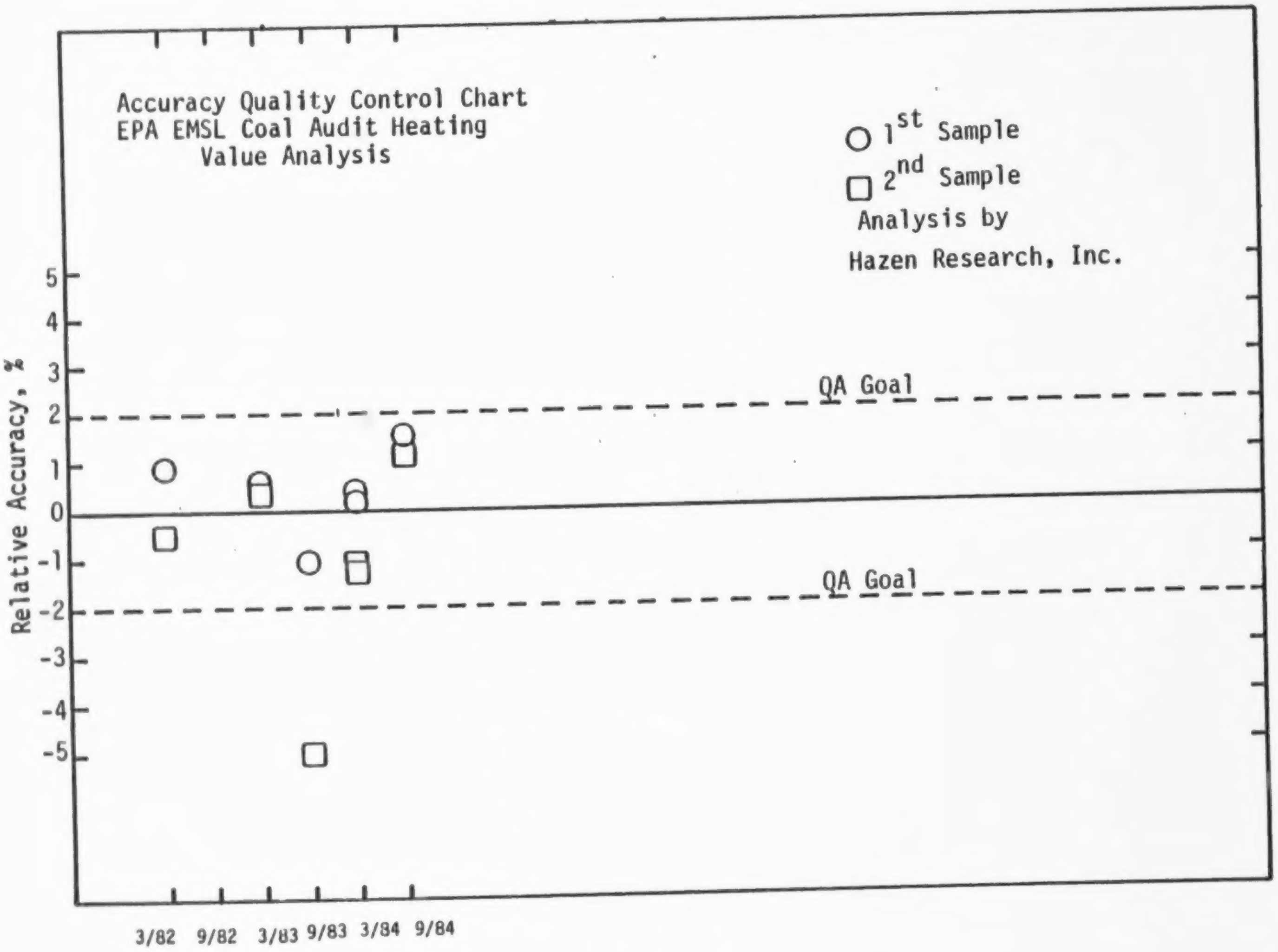

Figure A-14. Relative accuracy of heating value determinations.

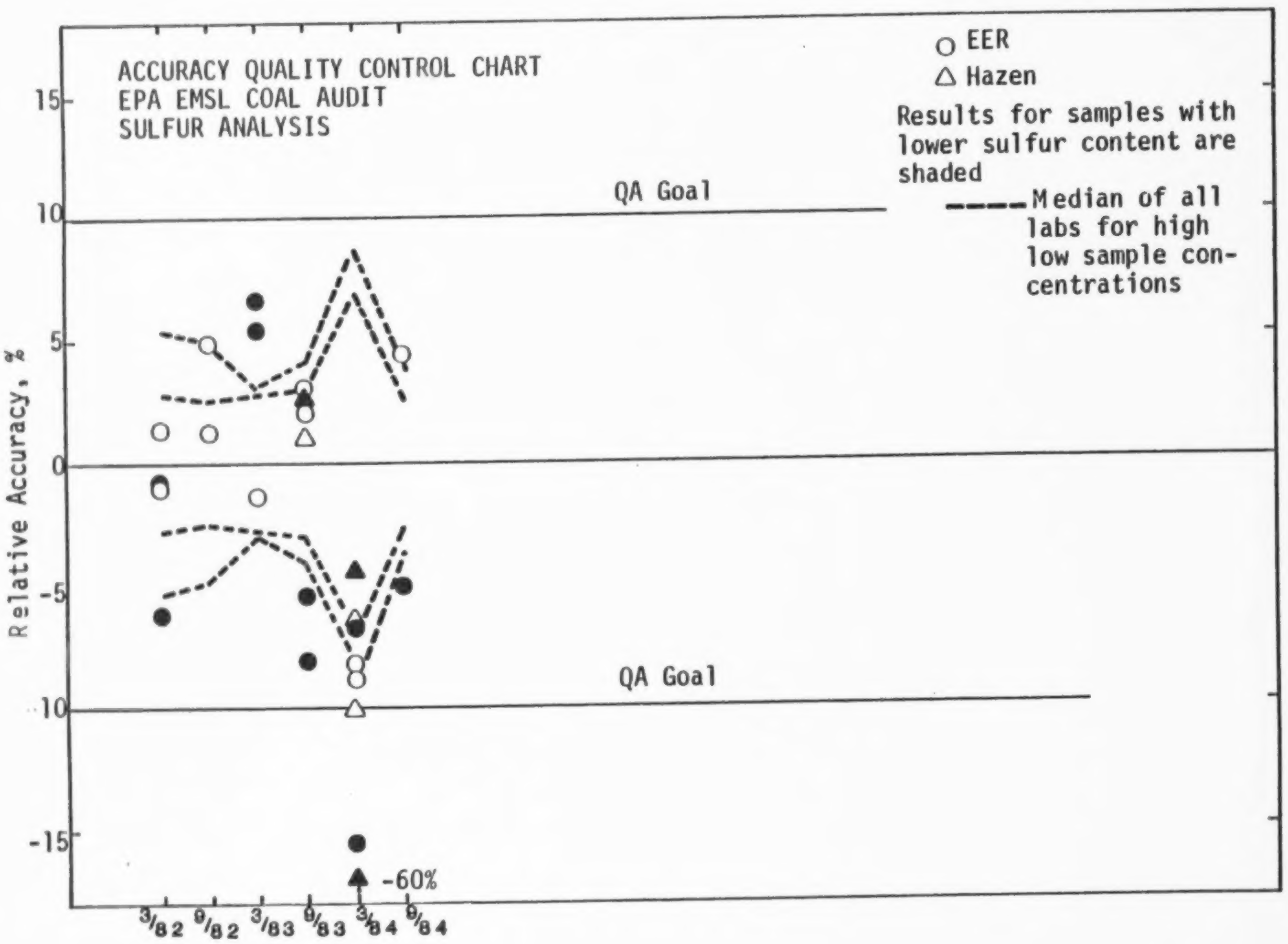

Figure A-15. Relative accuracy of coal sulfur.

TABLE A-6. SOLIDS ANALYSIS INTER-LABORATORY COMPARISON

	PARAMETER	EER ANALYSIS				STANDARD DEVIATION	HAZEN ANALYSIS	ACCURACY (%)
		1	2	3	AVG			
10-9-84	C	62.71	61.83	-	62.270	1.0	65.79	5.35
SAMPLE NO	H	4.10	4.17	-	4.140	1.2	4.00	3.38
115604	N	0.91	0.88	-	0.895	2.4	0.76	17.80
	Ash	8.85	8.46	8.86	8.720	2.6	8.99	3.00
10-9-84	C	63.60	62.18	-	62.890	1.6	66.41	5.30
SAMPLE NO	H	4.26	4.22	-	4.240	0.7	4.26	0.47
115610	N	1.05	0.85	-	0.950	14.9	0.78	21.80
	Ash	7.93	7.44	7.85	7.740	3.4	7.97	2.90
10-9-84	C	59.90	60.42	-	60.160	0.6	64.20	6.29
SAMPLE NO	H	4.04	4.09	-	4.065	0.9	3.75	8.40
115641	N	0.91	0.84	-	0.875	5.7	0.82	6.71
	Ash	11.60	11.46	-	11.530	0.9	11.62	0.77

AVG.	C	H	N	Ash
RELATIVE PRECISION,(%)	1.1	0.9	7.7	2.3
RELATIVE ACCURACY,(%)	5.65	4.08	15.44	2.22

Daily Routine

- Air Flow Distribution
- Air Preheat and Combustor Wall Temperature
- Gas Phase Species-Continuous Monitoring
- Pretest Oil Check
- Fuel Size Distribution
- Particulate Samples
- Time Limitation of Valid Data

System Verification

- Venturi Flowmeter Calibrations
- Instrument Performance Tests

The incorporation of the QA procedures into the test plan, ensured the documentation and collection of quality data resulting in verifiable and more accurate result and conclusions.

Table A-7 summarizes the precision and accuracy results of the system measurements as determined in accordance with the QAAP. For each of the measurements, the results are compared with the limits established in the program goal. The oil check is an additional QA procedure used by EER to determine the overall precision and accuracy of the complete facility measurement system including air and fuel flowrates, temperature, and emission monitors. The oil check is discussed in detail in section A.3.1. Instrument precision is determined from repeat calibrations throughout the entire test series. The following subsections discuss each of the QA procedures for the specific measurements.

A.3.1 Daily Routine Procedures

Routine calibrations and checks were performed on a daily basis to ensure that test data would be accurate, representative, and reproducible. Daily calibrations included air flow indication and flue gas analyzers.

TABLE A-7. SUMMARY OF PRECISION AND ACCURACY

Measurement	Precision (%)		Accuracy (%)	
	Actual	Goal	Actual	Goal
Air Distribution	3.70	4.0	3.22	10
Oil Check	2.29	-	2.98	10
Fuel Sieve-Sieves	-	10	4.81[1]	10
NO/NO_x	1.07[2]	2	6.96[1]	20
CO_2	1.72[2]	2	2.54	20
CO	3.61[2]	2	-	20
SO_2	2.93[2]	2	14.93	20
O_2	0.49[2]	2	6.02	20

1 - Basis: lb/10^6 Btu
2 - Basis: average over entire testing period:
Avg. Drift x 100 = % Precision

Other daily checks included verification of thermocouple operation, system oxygen balance while firing oil, pulverized coal size distribution, and time averaged valid data.

A.3.1.1 Air Flow Distribution

The distribution of combustion air between the burner passages was determined by direct measurement of the air flow rate to each passage using 18-inch venturi flowmeters. Each venturi was calibrated immediately prior to each test series using a standard pitot-tube. During testing, the pressure drop of the air through each venturi was continuously monitored using low pressure electronic transducers. Each transducer was calibrated manually prior to and immediately following the tests on each test day. The pressure differentials were in the range between 0-in. and approximately 3-in. H_2O. The calibrations were documented daily as shown in Table A-8 for a representative test day. The response from the transducers was calibrated within their linear range such that 1.0 mv response was equivalent to 3.8 in. H_2O pressure differential. From the calibrations, the percent drift in the transducers could be calculated to determine the precision and accuracy of the air flow measurements. Table A-9 summarizes the zero and calibration drift of the transducers during the second phase of testing. The zero drift was 0.36 percent and the calibration drift was 3.22 percent.

A.3.1.2 Air Preheat and Combustor Wall Temperatures

Type K (Chromel/Alumel) thermocouples were used to monitor the combustion air and furnace wall temperatures. ASTM Standard E231-77 specifies that the standard limit of error for Type K commercial thermocouples be $\pm$ 2°C or $\pm$ 0.75 percent between 0° and 1250°C. To assure that the thermocouples were functioning during testing, a continuous output of the temperatures was displayed on the computer data acquisition printout. In case of thermocouple malfunction, the damaged TC was immediately replaced. If, due to location restrictions, it was not practical to replace the TC while testing, it was replaced prior to the next day of testing.

TABLE A-8. SO_2 SAMPLE SYSTEM QA LOG

ANARAD SO_2 SAMPLE LOG DATE: 1-9-86

TIME	SAMPLE		ZERO		HIGH SPAN		LOW SPAN		SAMPLE		DRYER	CELL (°F)	OVEN (°F)	HEATED LINE (°F)	VARIAC	NEW FILTER INITIAL
	CELL PRESS.	ROTO	CELL	ROTO	CELL	ROTO	CELL	ROTO	CELL	ROTO						
			3.5	5.0	3.5	5.0					1-10-86					
			3.9	5.0	3.2	5.0										
12:29	3.4	5.0	3.4	5.0	3.4	5.0			3.4	5.0	40+	AMB.	286	242	Y	NO
13:12	3.4	5.0	3.4	5.0	3.4	5.0			3.4	5.0	40+	–	272	247		NO
14:21	3.4	5.0	3.8	5.0	3.4	5.0			3.4	5.0	40+		268	240		NO
	3.4	5.0	3.4	5.0					3.4	5.0	40+		268	240		NO

TABLE A-9. TYPICAL VENTURI FLOWMETER PRESSURE TRANSDUCER CALIBRATION

TRANSDUCER CALIBRATIONS

DATE: 1-16-86 FACILITY: LWS PROJECT: Mixing

TIME	Initial 7:15				Final 4:30											
TRANSDUCER/ VENTURI	ZERO		SPAN		ZERO		SPAN		ZERO		SPAN		ZERO		SPAN	
	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV
1	0.0	-.002	5.6	1.849	0.0	-.004	5.6	1.895								
2	↑	-.001	↑	1.851	↑	.005	↑	1.901								
3		-.001		1.848		-.001		1.899								
4		-.001		1.848		-.005		1.899								
5	↓	0.0	↓	1.847	↓	-.002	↓	1.842								
6	0.0	.001	5.6	1.847	0.0	.001	5.6	1.885								
7																
8																
9																
10																

A.3.1.3 Gas Phase Species

The exhaust gas phase species composition was measured using the LWS laboratory sampling system as outlined in Figure A-16. Flue gas was sampled immediately upstream of the LWS's SO_x and particulate scrubber system, thus ensuring that the flue gas sample was representative of the furnace effluent. A single sample probe which draws from the center of the duct was used. All materials in contact with the sample gas were glass, stainless steel, Teflon, and a small amount of Kel-F (valve seals). These materials have been demonstrated as essentially nonreactive to the gases measured over the temperature range involved in this system.

This system is generally satisfactory for most tests, but may result in measurement error when SO_2 and sorbents, such as limestone, are present. Therefore, an independent SO_2 sample system, described in Section A.2.5, was utilized. The critical temperatures of the SO_2 sample system were maintained and recorded in a daily log. In this system, a quartz filter was used to clean the gas sample from the particulates before it entered the instrument. The filter may introduce an error in SO_2 concentration measured during sorbent injection due to agglomeration of particles on the filter, thus creating a scrubbing effect independent of the injection parameters. Therefore, this filter was changed at least after every two tests of sorbent injection had been completed or as necessary to maintain a clean filter. During sorbent testing, baseline data points (with no sorbent) were taken immediately preceding sorbent injection. After the sorbent test was completed, the system was allowed to return to baseline before continuing with sorbent injection. Therefore, the relative SO_2 concentrations of the preceding and past test baseline remained constant. Hence, it was assured that no measured SO_2 loss was occurring during sorbent injection because of any scrubbing effects of the sample system.

Table A-10 lists the continuous gas analyzers used during these tests. To satisfy the desired accuracy, the instruments were operated according to EPA Performance Standards 2 and 3. Each instrument was calibrated with three certified gases; a zero gas and two span gases, at approximately 50 and 90

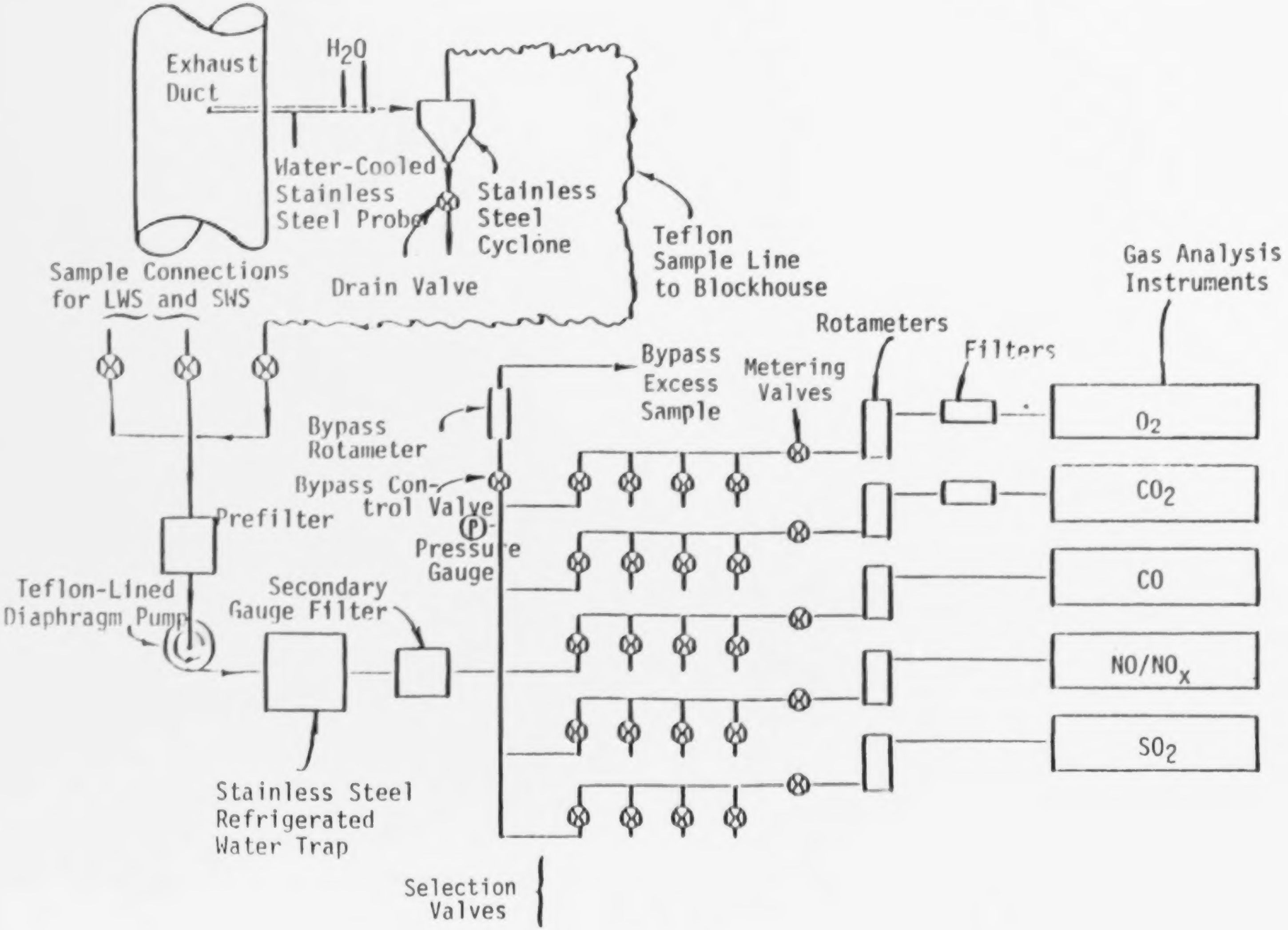
Exhaust Duct
H$_2$O
Water-Cooled Stainless Steel Probe
Stainless Steel Cyclone
Drain Valve
Teflon Sample Line to Blockhouse
Sample Connections for LWS and SWS
Gas Analysis Instruments
Rotameters
Filters
Bypass Excess Sample
Metering Valves
Bypass Rotameter
Bypass Control Valve
P
Pressure Gauge
Prefilter
Teflon-Lined Diaphragm Pump
Secondary Gauge Filter
Stainless Steel Refrigerated Water Trap
Selection Valves
O$_2$
CO$_2$
CO
NO/NO$_x$
SO$_2$

Figure A-16. LWS sample train.

TABLE A-10. CONTINUOUS GAS ANALYZERS

Gas Measured	Type of Instrument	Manufacturer	Model No.	Range
O_2	Paramagnetic	Beckman	755	10 percent
CO_2	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR 500 R	20 percent
CO	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR 500 R	500 ppm
NO_x	Chemiluminescent	Thermo Electron Corp.	10 AR	1000 ppm
SO_2	Long Path Nondispersive Ultraviolet (NDUV)	Anarad, Inc.	AR 50	6000 ppm

percent of scale. To increase accuracy and precision, the instruments were calibrated approximately every two hours during the test day. The instrument calibrations included electronically calibrating the instrument response to the data logger and the strip chart recorder, simultaneously. This ensured that the instrument, computer printout, and the strip chart were in agreement. The calibrations were documented in a calibration log, such as the example shown as Table A-11, as well as the computer printout and strip chart. This log provided data to evaluate the calibration drift of each instrument for each day of testing. Generally, if the calibration drift exceeded 4 percent during a calibration interval, the valid data obtained during that period were corrected for drift.

A.3.1.4 Pretest Oil Check and Coal Feedrate Determination

A pretest oil check was completed daily, prior to switching the system to coal. The oil check was used to warm the system up and oil check provided a QA check on the overall LWS process system. The oil check is the ratio between the calculated and measured load. The calculated load is a theoretical determination based on the heating value of the fuel oil and the measured oil flow rate. It is independent of the air flow system. The measured load is a function of the O_2 concentration measured in the exhaust, and the air and fuel flow rates. The resultant ratio indicates the overall accuracy of the measurement system: transducers, continuous monitoring instruments, thermocouples, and fuel flowmeters. The difference between the calculated and measured load had to be less than 10 percent in order to proceed with testing.

Figure A-17 shows the daily plot of the oil checks obtained throughout the test series. The accuracy and precision of the measurement system as determined by the oil check for December and January test series were 2.29 and 2.98 percent respectively. These values were both below the program objective of 10 percent.

The coal input feedrate was calculated using an oxygen balance and also a weigh belt feeder. The oil check oxygen balance verifies that the

TABLE A-11. DAILY INSTRUMENT CALIBRATION LOG

Date: 1-16-86 Facility: LWS Project: Mixing

Time:	8:35	10:15	12:00	13:45	15:40	16:25
O_2						
Initial Zero (Z_i)-Div/MV	0.0	-0.3	0.0	0.0	0.0	
Initial Span (S_i)-Div/MV	90.0	90.0	89.7	90.0	89.0	
Final Zero (Z_f)-Div		0.0	0.0	0.0	0.0	0.3
Final Span (S_f)-Div		90.0	90.0	90.0	90.0	90.0
Span Gas (G_s) % /Div	9.0%					
Zero Drift (%) = $\frac{Z_i-Z_f}{G_s}$		-0.33	0.0	0.0	0.0	0.33
Span Drift (%) = $\frac{S_i-S_f}{G_s}$		0.0	-0.33	0.0	-1.11	0.0
CO_2						
Initial Zero (Z_i)-Div/MV	0.0	0.0	0.0	0.0	0.0	
Initial Span (S_i)-Div/MV	75.0	65.0	74.0	73.0	75.0	
Final Zero (Z_f)-Div		0.0	0.0	0.0	0.0	0.0
Final Span (S_f)-Div		75.0	75.0	75.0	75.0	75.0
Span Gas (G_s)-%/Div	15.0%					
Zero Drift (%) = $\frac{Z_i-Z_f}{G_s}$		0.0	0.0	0.0	0.0	0.0
Span Drift (%) = $\frac{S_i-S_f}{G_s}$		-13.3	-1.33	-2.67	0.0	1.33
CO						
Initial Zero (Z_i)-Div/MV	0.0	-4.0	0.3	3.0	-2.0	
Initial Span (S_i)-Div/MV	50.0	49.0	52.0	49.2	50.0	
Final Zero (Z_f)-Div		0.0	0.0	0.0	0.0	6.0
Final Span (S_f)-Div		50.0	50.0	50.0	50.0	65.0
Span Gas (G_s)-PPM/Div	25 PPm					
Zero Drift (%) = $\frac{Z_i-Z_f}{G_s}$		-8.0	0.6	6.0	-4.0	12.0
Span Drift (%) = $\frac{S_i-S_f}{G_s}$		-2.0	4.0	-1.6	0.0	30.0
NO_x						
Initial Zero (Z_i)-Div/MV	0.0	0.0	0.0	0.0	0.0	
Initial Span (S_i)-Div/MV	79.0	82.2	79.0	80.0	79.0	
Final Zero (Z_f)-Div		0.0	0.0	0.0	0.0	0.0
Final Span (S_f)-Div		79.0	79.0	79.0	79.0	79.0
Span Gas (G_s)-PPM/Div	789.5 PPm					
Zero Drift (%) = $\frac{Z_i-Z_f}{G_s}$		0.0	0.0	0.0	0.0	0.0
Span Drift (%) = $\frac{S_i-S_f}{G_s}$		4.05	0.0	1.27	0.0	0.0

Time:	1018	1300	1345	1410	1504	1534	1553	1558	1616			
SO_2												
Initial Zero (Z_i)-Div/MV	0.0	2.0	2.0	1.3	0.0	0.8	0.2	0.5				
Initial Span (S_i)-Div/MV	58.0	54.0	60.0	58.0	56.5	59.8	59.8	59.0				
Final Zero (Z_f)-Div		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
Final Span (S_f)-Div		58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0			
Span Gas (G_s)-PPM/Div	34.95											
Zero Drift (%) = $\frac{Z_i-Z_f}{G_s}$		3.45	3.45	2.24	0.0	1.40	0.34	0.86	0.0			
Span Drift (%) = $\frac{S_i-S_f}{G_s}$		0.72	3.45	0.0	-2.59	3.10	3.10	1.72	0.0			

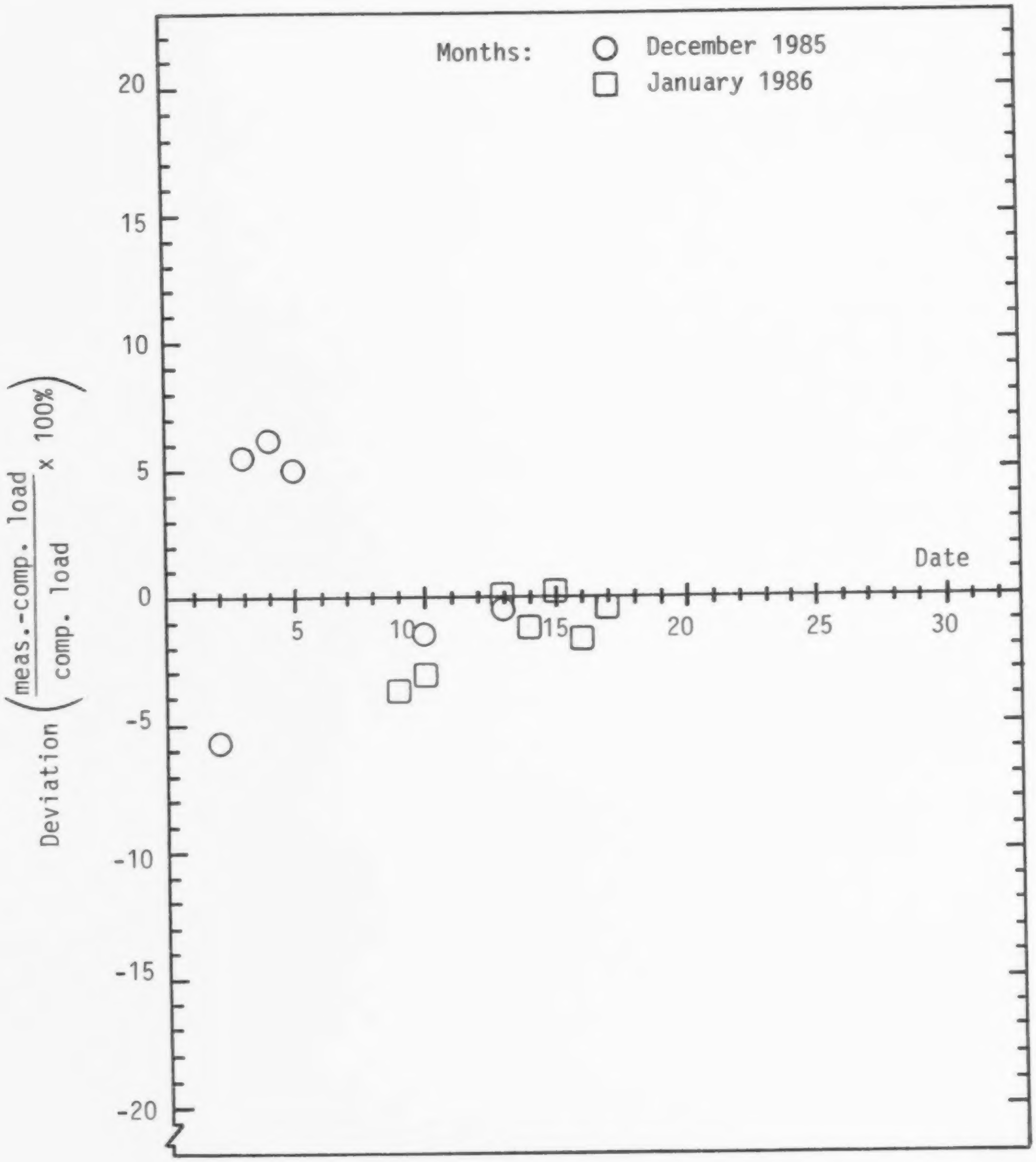

Figure A-17. Oil check summary.

calculation of the coal firing rate is justified. The weigh belt feeder also serves to confirm the calculation . The load cell of the feeder has an accuracy of ± 0.1 percent. However, it is necessary to calibrate the load cell dynamically and adjust the electronic set points according to the manufacturer's specification. The feeder was calibrated prior to the test series and during the tests as necessary after maintenance or repair.

A.3.1.5 Fuel Size Distribution

The coal fineness affects the combustion performance of the burner; therefore, it was necessary to determine the coal fineness daily. The coal sample was drawn isokinetically according to the procedures as outlined in ASTM Method D197 and the ASME Performance Test Code for Coal Pulverizers. The coal sample probe is shown in Figure A-18. An isokinetic sample is drawn by a vertical and horizontal traverse of the coal type at a sample location downstream of the pulverizer. A sample was taken daily for each coal type and firing rate. The recovery rate, as specified by the method, must be 100 percent ± 10 percent. After each sample, the recovery rate was calculated. If the recovery rate was not within the limits, another sample was taken if operating conditions allowed. After verifying a recovery rate of 100 ± 10 percent, the sample was analyzed for size distribution.

The main concern for burner performance was to ensure that the coal size distribution resulted in at least 70 percent passing through 200 mesh (75 μm). The sieves were standard ASTM sieves. During the test series the analysis was conducted using a commercial air sieve. The sieve was calibrated using the National Bureau of Standards Reference material SRM 1004. SRM 1004 is a set of calibrated glass beads with specific cumulative size distribution determined by microscopic measurement. The calibration results are summarized in Table A-12. The nominal size of 200 mesh sieve is 75 microns. However, all the openings of the sieve are not the same size. Therefore, by using the calibrated glass beads the effective opening of the sieve is determined. To accurately determine the calibration of the sieve, the same method of measurement was used during testing. For the test series a commercial air sieve was used with a relative accuracy of 4.81 percent.

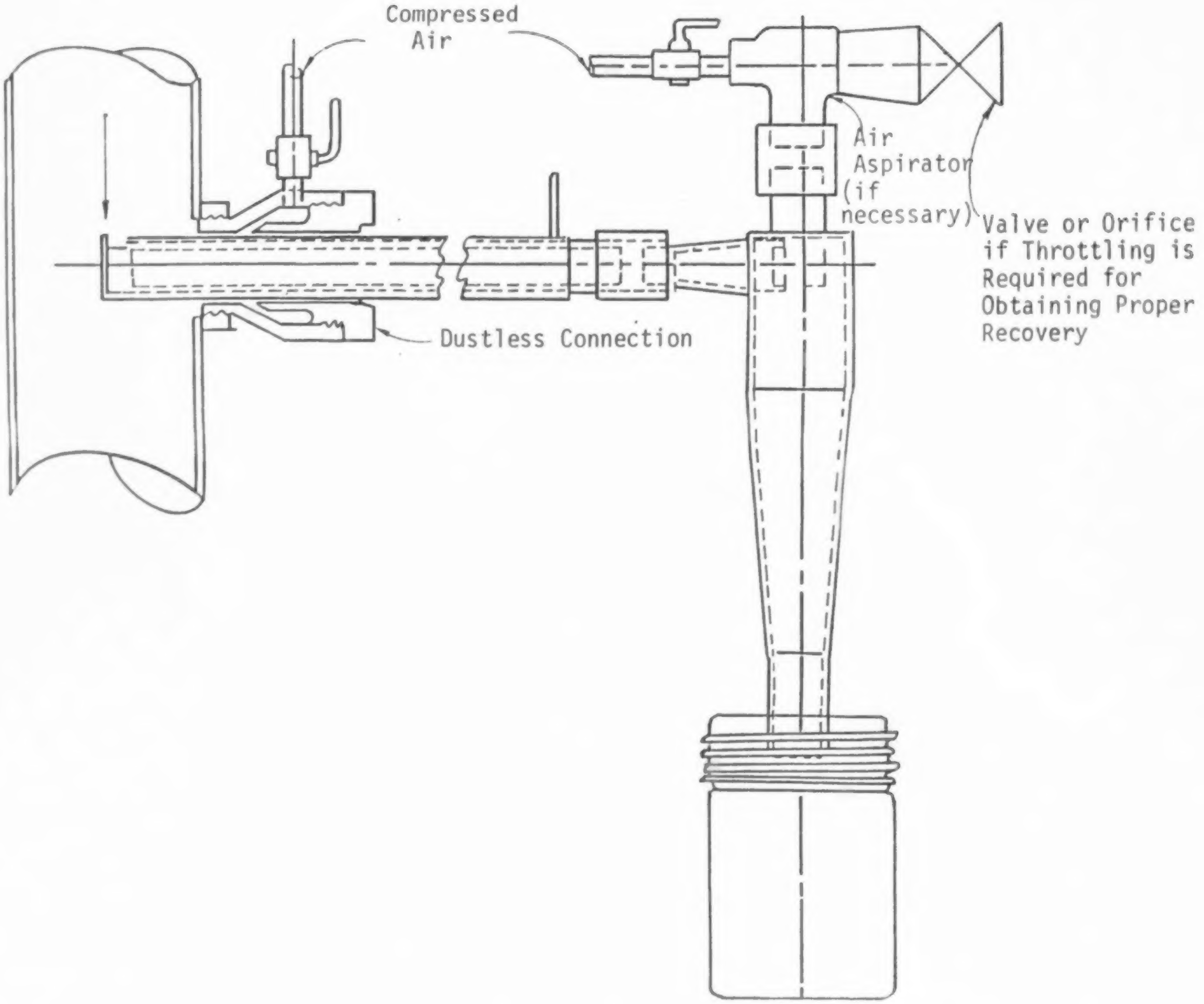
Compressed Air
Air Aspirator (if necessary)
Valve or Orifice if Throttling is Required for Obtaining Proper Recovery
Dustless Connection

Figure A-18. Pulverized coal sampling system.

TABLE A-12. SUMMARY OF ASTM SIEVE CALIBRATION

Sieve No.	Sieve Nominal Opening (Microns)	Weight % Finer (EER Sieves)	Weight % Finer (NSB-SRM)	Effective Sieve Opening (Microns)	Relative Accuracy (%)
200-A	75	46.26	49.0	71.39	4.81

A.3.1.6 Particulate Samples (Grab Sample)

Analysis of the fly ash is essential in determining the burner/furnace performance. Therefore, for all of the major test conditions during this test series, fly ash samples were collected to obtain representative samples. Two methods were utilized:

1. Grab Sample
2. High-Volume Bag House Filter

The grab sample was collected using a standard sampling system with an ejector and a small cyclone with the sample probe in the center of the exhaust duct. The high-volume bag house draws a representative sample into the bag house using an exhauster and with the particulate matter collected on the bags. Air pulses through the filter every 15 seconds causing the particulate to drop into the collection container. Prior to every test condition, the bag house was purged to ensure that the collected sample was representative of that specific test condition. Using percent carbon in the ash as a relative indicator of accuracy between the high volume sampler and grab sample resulted in an average relative accuracy of 9.3 percent. Since this was less than 10 percent, for most of the detailed analysis, the high-volume sample was used. This was due mainly to the large volume of sample which could be obtained during a short period of time in comparison to the grab sample.

A.3.1.7 Valid Data Acquisition

The outputs of all continuous instrumentation (flowrates, temperatures, analyzers, flowmeters, thermocouples, etc.) were input into a A/D Converter which was interfaced with the Hewlett Packard computer. The computer processed these data and provided a real-time indication of input and output parameters. For a given test condition, valid data point represents the values of the average inputs and outputs. These values were input manually entering these values into the computer. In addition, temperatures and flowrates were corrected as required to ensure that the results of the specific test included only valid data and conditions.

A.3.2 System Verification Procedures

During this test program, system verification procedures that were performed included venturi flowmeter calibrations and instrument performance tests. The accuracy and precision of both air flow and the concentrations of exhaust gas components were essential to achieving quality data.

A.3.2.1 Venturi Flowmeter Calibration and Leak Checks

Calibrations of the venturi flowmeters were performed prior to the start of testing. The relationship between the air flow rate and pressure drop across the venturi can be expressed as:

$$\dot{M} = K\ (\Delta P/T)^{1/2}$$

where: $\dot{M}$ = mass flowrate through the venturi, SCFM
P = pressure drop across the venturi, in H_2O
T = absolute air temperature, °R
K = the dimensional venturi

Calibrations were conducted for each venturi over a range of air flow rates, with the data reduced to the form of the above equation. These calibrations were incorporated into the data acquisition program used for this program. Records of the calibrations are maintained at EER.

The air flowrates measured by the venturis in the LWS system are remotely monitored. Pressure taps and thermocouples are mounted on each venturi flowmeter, with the pneumatic tubing and thermocouple lead wires running into the LWS control room. Because of the environment of heat and moisture surrounding the venturis during testing, leak checks of the pneumatic tubing from the venturi flowmeters to the pressure transducers in the control room were conducted periodically during the test program. Table A-13 shows an example of the pressure transducer calibration and drift

TABLE A-13. CALIBRATION DRIFT DETERMINATION OF PRESSURE TRANSDUCERS FOR AIR FLOW RATE CALCULATION

Initial Zero (MV)	Zero Error (MV)	Precision (% Difference)	Confidence Interval Zero (MV)	Zero Drift (%)	Initial Calibration (MV)	Calibration Error (MV)	Calibration Precision	Confidence Interval (MV)	Calibration Drift (%)	Final Calibration (MV)
0.0013	0.0062 ± 0.0077	0.35	0.0017	0.36	2.18 ± 0.35	0.049 ± 0.077	3.70	0.017	3.22	2.07 ± 0.26

1 - Reference ΔP using inclined manometer

determination. Pressure transducers were calibrated in the beginning and the end of each test day and in between as necessary.

A.3.2.2 Instrument Performance Tests

The LWS continuous monitoring system is operated according to EPA Specification 2 and 3. These specifications include instrument performance test guidelines. As part of the QA plan for this test series, an abbreviated instrument performance test was conducted. Table A-14 summarizes the results for the test series. The relative accuracy was determined by comparing the instrument values to values obtained using EPA Reference Methods. There is currently no performance specification for the CO monitor or standard reference method for CO determination. Therefore, relative accuracy for CO could not be determined, but the 2-hour drift test was conducted in accordance with the guidelines for the other analyzers. The results show that the relative accuracy for the O_2, CO_2 and NO_x instruments were within specifications. The increase in relative accuracy during the second phase of the NO_x tests is probably related to a decrease in number of samples due to sampling limitations and laboratory analysis problems. The decrease in number of samples generally reduces the statistical accuracy of a set of measurements. The relative accuracy of the DuPont SO_2 instrument was not within EPA specifications for Phase I. The result is biased by a large error, almost 28 percent, in one of the five Method 6 samples. The other four samples were in better agreement with the SO_2 concentration simultaneously measured by the DuPont analyzer. Excluding the sample with the large error improves the relative accuracy to 16.2 percent which is within EPA Performance Specification 2.

The O_2, CO_2, NO_x, and SO_2 instruments were within the specifications for zero and calibration drift for both test phases. The CO instrument had higher calibration drift than allowed for the other instruments. This may have been related to the high sensitivity of the instruments at high span values. This drift was probably also related to inherent problems with drift in NDIR instruments due to temperature fluctuations. The calibration error

TABLE A-14. INSTRUMENT PERFORMANCE TEST SUMMARY FOR 80×10^6 BTU/HR MIXING

Instrument/Manufacturer	Relative Accuracy (%)	EPA Specification (%)	Calibration Error (%)		EPA Specification (%)	2 Hr Drift Test (%)		EPA Specification (%)
			Mid	High		Zero	Calibration	
O_2--Beckman	6.02	≤20	2.13	0.78	≤5.0	0.17	0.77	≤0.5
CO_2--Anarad, Inc.	2.54	≤20	1.43	3.96	≤5.0	0.47	4.26	≤0.5
NO_2NO_x--TECO	6.96[1]	≤20	1.15	0.70	≤5.0	0.63	1.97	≤2.5
SO_2--Anarad, Inc.	14.93	≤20	1.63	2.48	≤5.0	1.56	2.28	≤2.5
CO--Anarad, Inc.	-	-	5.82	5.95	-	5.94	6.41	-

1 - Basis: lb/10^6 Btu

determines the linearity of the instruments. For each of the instruments the linearity was within acceptable limits established in the PEA specifications.

APPENDIX B. TOWER FURNACE DATA

DATA SUMMARY

Sorbent : Linwood AH

Date	Injection Location	T_{inj} °F	No of Jets	Jet Dia, in	J	Ca/S	ΔSO_2 %
11/14/85	Nose	2257	6	0.625	122	0.68	23.6
//	//	//	//	//	130	1.07	46
11/26/85	Nose	—	1 corner jet	0.875	242	0.64	6.0
''	''	—	''	''	275	1.07	17.0
11/26/85	Nose	2300	6	0.625	116	2.14	69.0
//	//	//	//	//	97	0.94	31.0
//	//	//	//	//	108	1.60	37.0
//	//	//	//	//	112	1.82	48.0
11/26/85	Nose	2300	6	0.625	116	2.14	45

DATA SUMMARY

Sorbent: Vicron 45-3

Date	Injection Location	T_{inj}, °F	No of Jets	Jet Dia, in.	J	Ca/S	ΔSO_2 %
11/22/85	Nose	2388	6	0.625"	141	2.22	34.72
"	"	"	"	"	149	2.55	40.1
11/22/85	Nose	2388	3	0.625"	201	0.47	26.0
"	"	"	"	"	553	2.08	20.9
"	"	"	"	"	621	1.58	23.0
11/21/85	Nose	2385	6	0.625"	121	2.53	47.5
"	"	"	"	"	102	1.58	29.5

DATA SUMMARY

Sorbent: Marblehead AH

Date	Injection Location	T_{inj}, °F	No of Jets	Jet Dia, in.	J	Ca/S	ΔSO_2 %
11/21/85	Nose	2390	6	0.625"	120	2.36	68.0
//	//	//	//	//	88.3	0.40	19.0

DATA SUMMARY

Sorbent: Marblehead AH

Date	Injection Location	T_{inj}, °F	No of Jets	Jet Dia, in.	J	Ca/S	ΔSO_2 %
11/21/85	Nose Front Wall	2390	6	0.625	120.3	2.36	68
//	//	//	//	//	88.3	0.4	19

DATA SUMMARY

Sorbent: Linwood AH

Date	Injection Location	T_{inj}, °F	No of Jets	Jet Dia, in.	J	Ca/S	ΔSO_2 %
12/4/85	Front wall nose level	2200	One center jet	2.0"	29	0.89	16.5
"	"	"	"	"	134	1.65	29.5
12/4/85	Front wall nose level	2200	One corner jet	0.875"	1255	2.14	35.5
11/9/85	Front Wall Nose Level	2264°F	6	0.625"	139	3.35	72
"	"	"	"	"	84	2.74	59
"	"	"	"	"	131.	2.87	73
11/19/85	+0.5H	2354°F	6	0.625"	123.	2.36	42
"	"	"	"	"	144.	3.65	67

DATA SUMMARY

Sorbent: Linwood AH

Date	Injection Location	T_{inj}, °F	No of Jets	Jet Dia, in.	J	Ca/S	ΔSO_2 %
11/20/85	Nose	2318	Center Port only	0.875	480	3.21	70.5
"	"	"	"	"	340	1.50	54.9
11/20/85	Nose	2318	1 corner jet	0.875	201	1.29	51.5
"	"	"	"	"	257	1.71	44.0
11/20/85	Side wall below nose	2318	1 jet near front wall	0.875	188	1.07	50.0

DATA SUMMARY

Sorbent: Linwood AH

Date	Injection Location	T inj. °F	No of Jets	Jet Dia, in	J	Ca/S	ΔSO_2 %
11/15/85	Nose	2473	6	0.625	180	1.74	48
//	//	2473	//	//	153	1.07	21
11/18/85	//	2374	//	//	140	1.90	52
//	//	2430	//	//	133	1.67	39
11/13/85	//	2366	//	//	131	3.48	78
11/18/85	Nose	2372	6	0.625	113	2.45	74
//	//	2430	//	//	99	1.67	35
//	//	2264	//	//	125	0.82	20
11/13/85	//	2366	//	//	87	0.86	13.4 *
11/12/85	//	2332	//	//	88	1.73	49 *
//	//	2332	//	//	82	1.56	47 *

* Firing with coal & gas simultaneously. Baseline SO_2 = 2200 ppm @ 0 0% O_2 instead of 2800 ppm.

DATA SUMMARY

Sorbent : Linwood AH

Date	Injection Location	$T_{inj.}$ °F	No of Jets	Jet Dia, in	J	Ca/S	ΔSO_2 %
11/18/85	Nose	2388	6	0.625	66	2.06	49
11/12/85	"	2332	6	"	51	0.96	26
11/7/85	+ 0.5 H	T_{nose} = 2192 T_{inj} = 2015	6	0.625	97	0.6	19
"	"	"	6	"	106	1.14	52
"	"	"	6	"	119	1.88	53
11/4/85	+ 0.5 H	T_{nose} = 2233	6	0.625	58	0.62	17.7
"	"	T_{nose} = 2318	6	"	35	1.5	42
"	"	T_{inj} = 2214	6	"	33	2.2	51

DATA SUMMARY

Sorbent : Linwood AH

Date	Injection Location	$T_{inj.}$ °F	No of Jets	Jet Dia, in	J	Ca/S	ΔSO_2 %
11/1/85	Nose	2190	3	0.625	81	1.07	34.5
10/31/85	〃	2181	〃	〃	94	2.14	46.5
10/30/85	〃		〃	〃	91	0.54	31.5
〃	〃		〃	〃	114	1.61	43
〃	〃		〃	〃	110	1.46	37.6

APPENDIX C. LWS FURNACE DATA

```
DATE          :  12-04-85               NOZ'L.DES.    :  BASELINE
SYSTEM        :  LWS-INS.               SEC.CONFGN    :  ASP
BURNER        :  XCL-80 MKB             SPREADER      :  DIFFUSER
FUEL          :  OHIO-PITT8             OIL CHECK     :  6.16
-------------------------------------------------------------------------------------------------------------------------------------------------------------
              LOAD            PRIM  V -2  V -3  V -4  V -5  V -6  TOTAL      PRIM     STA   OFA      PRIM  SFC1  SFC2(TOTAL)     O2    CO     CO2     NO     SO2
PT#   TIME    MBTU/HR   TA                      FLOW SCFM                       FLOW SCFM                   SR (CUM)                              MEASURED
 OIL          CALC      SCFM                                                    TEMP (F)                                                       CORR TO 0% O2
(%)   LOAD    MEAS                              TEMP (F)                     VELOCITY (FT/SEC)                                                 CORR TO 3% O2
-------------------------------------------------------------------------------------------------------------------------------------------------------------

 441  12:52:49  80.0  13585   2256  3480  3463  3532  3496     0  16226      2256      0     0       0.17  0.47  1.19            3.5   25.0   14.5  280.0  2640.0
                                                                              150      0     0                                     0.0   30.0   17.4  336.0  3168.0
 0.0  0.0       85.2           534   605   603   605   602   482              63      0     0                                     3.0   25.7   14.9  288.0  2715.4
KTRON= 6900  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  OUT REG= 40 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX= 4.50 in H2O  FURNACE P= 0.22 in H2O  COAL P= 4.50 in H2O  MILL IN= 458 F  MILL OUT= 157 F
T WBOX= 544 F  SAMPLE= 1223 F  EXIT1=1811 F  EXIT2=1851 F  EXIT3=1811 F  EXIT4=1864 F  EXIT5=1837 F  EXIT6=1866 F  EXIT7=1521 F  EXIT8=1573 F  EXIT9=1544 F  EXIT10=1570 F  SP(13')= 2264 F  SP(19')= 2061 F  SP(27')=  203 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0   BASELINE FULL LOAD
VALID DATA POINT #  1   ELAPSED TIME, MIN  7   RECORD ON TRK  0   FILE  1

 528  13:49:35  79.8  13554   2272  3467  3458  3522  3469     0  16188      2272      0     0       0.17  0.48  1.19            3.5   25.0   15.6  270.0  2520.0
                                                                              150      0     0                                     0.0   30.0   18.7  324.0  3024.0
 0.0  0.0       83.9           528   605   603   605   602   481              63      0     0                                     3.0   25.7   16.0  277.7  2592.0
KTRON= 6800  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  OUT REG= 40 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX= 4.50 in H2O  FURNACE P= 0.22 in H2O  COAL P= 4.50 in H2O  MILL IN= 452 F  MILL OUT= 160 F
T WBOX= 587 F  SAMPLE= 1230 F  EXIT1=1762 F  EXIT2=1646 F  EXIT3=1790 F  EXIT4=1840 F  EXIT5=1787 F  EXIT6=1842 F  EXIT7=1517 F  EXIT8=1572 F  EXIT9=1533 F  EXIT10=1556 F  SP(13')= 2260 F  SP(19')= 2040 F  SP(27')= -130 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0   BASELINE FULL LOAD
VALID DATA POINT #  2   ELAPSED TIME, MIN  7   RECORD ON TRK  0   FILE  2
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DATE        :   12-05-85                                  NOZ'L.DES.   :   BASELINE
SYSTEM      :   LWS-INS.                                  SEC.CONFGN   :   ASP
BURNER      :   XCL-80  MKB                               SPREADER     :   DIFFUSER
FUEL        :   OHIO-PITT8                                OIL  CHECK   :   4.98

              LOAD            PRIM   V -2   V -3   V -4   V -5   V -6   TOTAL          PRIM     STA     OFA            PRIM   SEC1   SEC2(TOTAL)          O2     CO     CO2     NO     SO
PT#   TIME   MBTU/HR   TA                          FLOW SCFM                                 FLOW SCFM                         SR (CUM)                                  MEASURED
  OIL         CALC     SCFM                                                                   TEMP (F)                                                                  CORR TO 0% O2
(%)   LOAD    MEAS                                 TEMP (F)                              VELOCITY (FT/SEC)                                                              CORR TO 3% O2

 477  13:45:11  79.2   13443    2361   3418   3399   3470   3498      0   16146          2361       0       0            0.18   0.48   1.20                 3.6    30.0   14.6   260.0  2520.0
                                                                                          143       0       0                                                 0.0    36.2   17.6   313.8  3041.4
 0.0   0.0      83.3             493    600    600    603    601    465                    65       0       0                                                 3.0    31.0   15.1   269.0  2606.9
KTRON= 6750   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.50 in H2O   FURNACE P=  0.25 in H2O   COAL P=  4.50 in H2O   MILL IN=  424 F   MILL OUT=  152 F
T WBOX=    0 F  SAMPLE= 1246 F  EXIT1=1790 F  EXIT2=1849 F  EXIT3=1765 F  EXIT4=1833 F  EXIT5=1773 F  EXIT6=1831 F  EXIT7=    0 F  EXIT8=1552 F  EXIT9=1614 F  EXIT10=1614 F  SP(13')= 2276 F  SP(19')= 1980 F  SP(27')= 1789 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00     J=   0    BASELINE FULL LOAD
VALID DATA POINT #   1   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE   3

 508  14:05:14  77.7   13181    2366   3386   3423   3490   3523      0   16479          2366     290       0            0.18   0.52   1.25                 4.3    25.0   14.0   280.0  1590.0
                                                                                          142     114       0                                                 0.0    31.4   17.6   352.1  1999.4
 0.0   0.0      83.3             497    601    600    604    603    468                    65      20       0                                                 3.0    26.9   15.1   301.8  1713.6
KTRON= 6750   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.50 in H2O   FURNACE P=  0.25 in H2O   COAL P=  4.50 in H2O   MILL IN=  425 F   MILL OUT=  151 F
T WBOX=    0 F  SAMPLE= 1255 F  EXIT1=1766 F  EXIT2=1811 F  EXIT3=1734 F  EXIT4=1806 F  EXIT5=1756 F  EXIT6=1809 F  EXIT7=    0 F  EXIT8=1550 F  EXIT9=1619 F  EXIT10=1595 F  SP(13')= 2257 F  SP(19')= 1990 F  SP(27')= 1741 F
SORBENT= LINWOOD     19FT. INJECTION     SORBENT LBS/HR= 369     SORBENT VELOCITY=  20 FT/SEC     SORBENT AIR FLOW=  290  SCFM    [Ca]/[S]=  0.69     J=  45    TEMP INJ(19ft)= 114 F        LINWOOD AT 19FT LEVEL
VALID DATA POINT #   2   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE   4

 592  15:06:03  77.0   13067    2348   3359   3314   3396   3441      0   16148          2348     290       0            0.18   0.51   1.24                 4.1    22.0   14.6   270.0  2280.0
                                                                                          142       0       0                                                 0.0    27.3   18.1   335.5  2833.1
 0.0   0.0      83.3             503    609    608    611    609    479                    65       0       0                                                 3.0    23.4   15.6   287.6  2428.4
KTRON= 6750   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.50 in H2O   FURNACE P=  0.25 in H2O   COAL P=  4.50 in H2O   MILL IN=  434 F   MILL OUT=  147 F
T WBOX=    0 F  SAMPLE= 1245 F  EXIT1=1758 F  EXIT2=1811 F  EXIT3=1737 F  EXIT4=1799 F  EXIT5=1754 F  EXIT6=1804 F  EXIT7=    0 F  EXIT8=1543 F  EXIT9=1611 F  EXIT10=1594 F  SP(13')= 2255 F  SP(19')= 2022 F  SP(27')= 1665 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   3   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE   5

 614  15:22:54  81.1   13758    2345   3334   3353   3432   3429      0   16162          2345     268       0            0.17   0.49   1.17                 3.2    25.0   15.4   260.0  1560.0
                                                                                          144     118       0                                                 0.0    29.5   18.2   306.7  1840.4
 0.0   0.0      83.3             508    612    611    613    613    487                    65      18       0                                                 3.0    25.3   15.6   262.9  1577.5
KTRON= 6750   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.50 in H2O   FURNACE P=  0.25 in H2O   COAL P=  4.50 in H2O   MILL IN=  436 F   MILL OUT=  154 F
T WBOX=    0 F  SAMPLE= 1250 F  EXIT1=1783 F  EXIT2=1853 F  EXIT3=1785 F  EXIT4=1851 F  EXIT5=1791 F  EXIT6=1849 F  EXIT7=    0 F  EXIT8=1586 F  EXIT9=1651 F  EXIT10=1628 F  SP(13')= 2300 F  SP(19')= 2051 F  SP(27')= 1698 F
SORBENT= LINWOOD     19FT. INJECTION     SORBENT LBS/HR= 927     SORBENT VELOCITY=  18 FT/SEC     SORBENT AIR FLOW=  268  SCFM    [Ca]/[S]=  1.66     J=  52    TEMP INJ(19ft)= 118 F        LINWOOD AT 19FT LEVEL
VALID DATA POINT #   4   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE   6

 639  15:43:22  79.1   13421    2345   3377   3303   3432   3422      0   16119          2345     239       0            0.17   0.50   1.20                 3.6    22.0   15.0   270.0  2370.0
                                                                                          143       0       0                                                 0.0    26.6   18.1   325.9  2860.3
 0.0   0.0      83.3             508    613    612    614    613    498                    65       0       0                                                 3.0    22.8   15.5   279.3  2451.7
KTRON= 6750   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.50 in H2O   FURNACE P=  0.25 in H2O   COAL P=  4.50 in H2O   MILL IN=  439 F   MILL OUT=  142 F
T WBOX=    0 F  SAMPLE= 1259 F  EXIT1=1780 F  EXIT2=1842 F  EXIT3=1787 F  EXIT4=1841 F  EXIT5=1777 F  EXIT6=1834 F  EXIT7=2303 F  EXIT8=1575 F  EXIT9=1638 F  EXIT10=1631 F  SP(13')= 2270 F  SP(19')= 2090 F  SP(27')= 1603 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   5   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE   7

 650  15:52:40  75.5   12808    2345   3367   3353   3417   3489      0   16202          2345     231       0            0.18   0.52   1.27                 4.5    33.0   15.2   270.0  1320.0
                                                                                          145     115       0                                                 0.0    42.0   19.3   343.6  1680.0
 0.0   0.0      83.3             502    612    612    614    613    498                    65      16       0                                                 3.0    36.0   16.6   294.5  1440.0
KTRON= 6750   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.50 in H2O   FURNACE P=  0.25 in H2O   COAL P=  4.50 in H2O   MILL IN=  433 F   MILL OUT=  157 F
T WBOX=    0 F  SAMPLE= 1272 F  EXIT1=1796 F  EXIT2=1844 F  EXIT3=1768 F  EXIT4=1840 F  EXIT5=1787 F  EXIT6=1840 F  EXIT7=2120 F  EXIT8=1581 F  EXIT9=1648 F  EXIT10=1641 F  SP(13')= 2257 F  SP(19')= 2012 F  SP(27')= 1684 F
SORBENT= LINWOOD     19FT. INJECTION     SORBENT LBS/HR=1674     SORBENT VELOCITY=  16 FT/SEC     SORBENT AIR FLOW=  231  SCFM    [Ca]/[S]=  3.23     J=  55    TEMP INJ(19ft)= 115 F        LINWOOD AT 19FT LEVEL
VALID DATA POINT #   6   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE   8
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DATE          :   12-10-85                                    NOZ'L.DES.   :   BASELINE
SYSTEM        :   LWS-INS.                                    SEC.CONFGN   :   ASP
BURNER        :   XCL-80 MKB                                  SPREADER     :   DIFFUSER
FUEL          :   OHIO-PITT8                                  OIL CHECK    :   -1.42
---------------------------------------------------------------------------------------------------------------------------------------------------
              LOAD                PRIM   V-2    V-3    V-4    V-5    V-6    TOTAL        PRIM      STA     OFA           PRIM   SFC1  SFC2(TOTAL)        O2     CO     CO2      NO     SO2
PT#   TIME    MBTU/HR    TA                              FLOW SCFM                          FLOW SCFM                          SR (CUM)                          MEASURED
 OIL          CALC      SCFM                                                                TEMP (F)                                                          CORR TO 0% O2
(%)   LOAD    MEAS                                       TEMP (F)                        VELOCITY (FT/SEC)                                                    CORR TO 3% O2
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 342  10:56:00  78.1   13249      2439   3297   3312   3284   3280     0   15913        2439      301      0            0.18   0.51   1.20             3.6    15.0    15.2   270.0  2400.0
                                                                                        137        0      0                                             0.0    18.1    18.3   325.9  2896.6
 0.0   0.0      84.6               443    653    650    653    649    461                67        0      0                                             3.0    15.5    15.7   279.3  2482.0
KTRON= 6850   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  377 F   MILL OUT=  145 F
T WBOX=  494 F  SAMPLE= 1234 F  EXIT1=1741 F  EXIT2=1834 F  EXIT3=1766 F  EXIT4=1830 F  EXIT5=1803 F  EXIT6=1834 F  EXIT7=   0 F  EXIT8=1610 F  EXIT9=1571 F  EXIT10=1569 F  SP(13')= 2244 F  SP(19')= 2054 F  SP(27')= 1654 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   1   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE   9

 361  11:12:17  79.0   13413      2487   3360   3293   3296   3284     0   16020        2487      301      0            0.19   0.50   1.19             3.5    25.0    15.2   270.0  1680.0
                                                                                        137      104      0                                             0.0    30.0    18.2   324.0  2016.0
 0.0   0.0      84.6               440    660    659    662    658    447                68       20      0                                             3.0    25.7    15.6   277.7  1728.0
KTRON= 6850   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  377 F   MILL OUT=  149 F
T WBOX=  501 F  SAMPLE= 1250 F  EXIT1=1772 F  EXIT2=1831 F  EXIT3=1795 F  EXIT4=1843 F  EXIT5=1799 F  EXIT6=1827 F  EXIT7=   0 F  EXIT8=1561 F  EXIT9=1596 F  EXIT10=1581 F  SP(13')= 2239 F  SP(19')= 2030 F  SP(27')=  129 F
SORBENT= LINWOOD      19FT. INJECTION     SORBENT LBS/HR= 521     SORBENT VELOCITY=  20 FT/SEC     SORBENT AIR FLOW=  301  SCFM     [Ca]/[S]=  0.96     J=  50    TEMP INJ(19ft)= 104 F        LINWOOD AT 19FT LEVEL
VALID DATA POINT #   2   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  10

 449  12:11:02  78.5   13317      2472   3340   3278   3295   3281     0   15986        2472      232      0            0.19   0.50   1.19             3.5    25.0    15.2   270.0  2340.0
                                                                                        136        0      0                                             0.0    30.0    18.2   324.0  2808.0
 0.0   0.0      86.4               440    666    664    666    663    467                67        0      0                                             3.0    25.7    15.6   277.7  2406.9
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  375 F   MILL OUT=  146 F
T WBOX=  509 F  SAMPLE= 1254 F  EXIT1=1810 F  EXIT2=1844 F  EXIT3=1796 F  EXIT4=1850 F  EXIT5=1802 F  EXIT6=1839 F  EXIT7=   0 F  EXIT8=1560 F  EXIT9=1601 F  EXIT10=1601 F  SP(13')= 2233 F  SP(19')= 2063 F  SP(27')= 1724 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   3   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  11

 493  12:43:53  81.9   13904      2463   3426   3380   3369   3353     0   16245        2463      253      0            0.18   0.49   1.17             3.1    25.0    15.6   275.0  1500.0
                                                                                        130       96      0                                             0.0    29.3    18.3   322.6  1759.0
 0.0   0.0      86.4               439    664    661    664    659    451                67       17      0                                             3.0    25.1    15.7   276.5  1508.4
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  370 F   MILL OUT=  139 F
T WBOX=  506 F  SAMPLE= 1259 F  EXIT1=1781 F  EXIT2=1832 F  EXIT3=1770 F  EXIT4=1830 F  EXIT5=1774 F  EXIT6=1816 F  EXIT7=   0 F  EXIT8=1563 F  EXIT9=1592 F  EXIT10=1585 F  SP(13')= 2235 F  SP(19')= 2037 F  SP(27')= 1300 F
SORBENT= LINWOOD      19FT. INJECTION     SORBENT LBS/HR=1651     SORBENT VELOCITY=  17 FT/SEC     SORBENT AIR FLOW=  253  SCFM     [Ca]/[S]=  2.93     J=  59    TEMP INJ(19ft)=  96 F        LINWOOD AT 19FT LEVEL
VALID DATA POINT #   4   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  12

 528  13:08:08  79.4   13482      2406   3382   3317   3330   3367     0   16102        2406      300      0            0.18   0.50   1.19             3.5    27.0    15.2   270.0  2340.0
                                                                                        130        0      0                                             0.0    32.4    18.2   324.0  2808.0
 0.0   0.0      87.6               441    667    664    665    662    473                65        0      0                                             3.0    27.8    15.6   277.7  2406.9
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  372 F   MILL OUT=  137 F
T WBOX=  544 F  SAMPLE= 1261 F  EXIT1=1801 F  EXIT2= 463 F  EXIT3=1793 F  EXIT4=1856 F  EXIT5=1794 F  EXIT6=1841 F  EXIT7=   0 F  EXIT8=   0 F  EXIT9=1607 F  EXIT10=1592 F  SP(13')= 2260 F  SP(19')= 2117 F  SP(27')= 1770 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   5   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  13

 587  13:47:07  78.1   13262      2507   3331   3230   3237   3315     0   15929        2507      301      0            0.19   0.51   1.20             3.6    35.0    14.8   265.0  1500.0
                                                                                        132      106      0                                             0.0    42.2    17.9   319.8  1810.3
 0.0   0.0      87.6               438    670    668    670    665    461                68       20      0                                             3.0    36.2    15.3   274.1  1551.7
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DFG   IN RFG =  30 (CW)DFG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  371 F   MILL OUT=  143 F
T WBOX=  539 F  SAMPLE= 1260 F  EXIT1=1565 F  EXIT2=1838 F  EXIT3=1778 F  EXIT4=1840 F  EXIT5=1760 F  EXIT6=1829 F  FXIT7=   0 F  EXIT8=   0 F  EXIT9=1588 F  EXIT10=1591 F  SP(13')= 2245 F  SP(19')= 2114 F  SP(27')= 1744 F
SORBENT= LINWOOD      23FT. INJECTION     SORBENT LBS/HR= 545     SORBENT VELOCITY=  20 FT/SEC     SORBENT AIR FLOW=  301  SCFM     [Ca]/[S]=  1.01     J=  51    TEMP INJ(23ft)= 106 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #   6   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  14
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DATE          :   12-10-85                        NOZ'L.DES.    :   BASELINE
SYSTEM        :   LWS-INS.                        SEC.CONFGN    :   ASP
BURNER        :   XCL-80 MKB                      SPREADER      :   DIFFUSER
FUEL          :   OHIO-PITT8                      OIL CHECK     :   -1.42
--------------------------------------------------------------------------------------------------------------------------------------------
              LOAD              PRIM   V -2   V -3   V -4   V -5   V -6   TOTAL        PRIM     STA    OFA          PRIM   SEC1   SEC2(TOTAL)         02     CO     CO2     NO     SO
PT0  TIME    MBTU/HR    TA                            FLOW SCFM                                FLOW SCFM                        SR (CUM)                                  MEASURED
  OIL         CALC     SCFM                                                                    TEMP (F)                                                                CORR TO 0% 02
(%)  LOAD     MEAS                                    TEMP (F)                              VELOCITY (FT/SEC)                                                          CORR TO 3% 02
--------------------------------------------------------------------------------------------------------------------------------------------

 637  14:23:58  77.3   13129    2357   3386   3317   3319   3289      0   15940         2357     280      0           0.18   0.51   1.21               3.0   20.0   14.4   270.0  2280.
                                                                                       129       0      0                                             0.0   24.4   17.6   329.7  2783.
 0.0   0.0      87.6             445    669    667    668    663    467                   64       0      0                                             3.0   20.9   15.1   282.6  2386.
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  375 F   MILL OUT=  142 F
T WBOX=  520 F  SAMPLE= 1280 F  EXIT1=1527 F  EXIT2=1958 F  EXIT3=1059 F  EXIT4=1923 F  EXIT5=1847 F  EXIT6=1890 F  EXIT7=   0 F  EXIT8=   0 F  EXIT9=1646 F  EXIT10=1670 F  SP(13')= 2283 F  SP(19')= 2204 F  SP(27')= 1807 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0 SCFM     [Ca]/[S]=  0.00     J=  0    BASELINE
VALID DATA POINT #  7   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  15

 659  14:41:16  83.4   14160    2489   3459   3450   3431   3435      0   16543         2489     280      0           0.18   0.49   1.17               3.1   20.0   15.0   275.0  1300.
                                                                                       131     100      0                                             0.0   23.5   17.6   322.6  1619.
 0.0   0.0      87.6             440    666    664    665    661    477                   67      18      0                                             3.0   20.1   15.1   276.5  1307.
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  372 F   MILL OUT=  140 F
T WBOX=  543 F  SAMPLE= 1300 F  EXIT1=1814 F  EXIT2=1803 F  EXIT3=1841 F  EXIT4=1914 F  EXIT5=1839 F  EXIT6=1901 F  EXIT7=   0 F  EXIT8=   0 F  EXIT9=1660 F  EXIT10=1642 F  SP(13')= 2301 F  SP(19')= 2211 F  SP(27')=  516 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR=1096     SORBENT VELOCITY=  10 FT/SEC     SORBENT AIR FLOW=  280  SCFM     [Ca]/[S]=  1.91     J=  56    TEMP INJ(23ft)= 100 F
VALID DATA POINT #  8   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE  22

 693  15:07:10  79.0   13405    2493   3405   3325   3360   3365      0   16191         2493     235      0           0.19   0.50   1.21               3.7   10.0   14.8   290.0  2250.
                                                                                       134       0      0                                             0.0   12.1   18.0   352.0  2731.
 0.0   0.0      87.6             439    664    663    665    661    472                   68       0      0                                             3.0   10.4   15.4   301.7  2341.
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  375 F   MILL OUT=  143 F
T WBOX=  541 F  SAMPLE= 1272 F  EXIT1=1442 F  EXIT2=1871 F  EXIT3=1813 F  EXIT4=1876 F  EXIT5=1809 F  EXIT6=1856 F  EXIT7=   0 F  EXIT8=   0 F  EXIT9=1627 F  EXIT10=1600 F  SP(13')= 2275 F  SP(19')= 2250 F  SP(27')= 1660 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0 SCFM     [Ca]/[S]=  0.00     J=  0    BASELINE
VALID DATA POINT #  9   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE  17

 710  15:17:41  80.6   13687    2466   3291   3349   3265   3296      0   15903         2466     235      0           0.18   0.49   1.16               3.0   20.0   15.2   285.0  1200.0
                                                                                       132     101      0                                             0.0   23.3   17.7   332.5  1400.0
 0.0   0.0      87.6             442    668    666    667    663    474                   67      15      0                                             3.0   20.0   15.2   285.0  1200.0
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  372 F   MILL OUT=  140 F
T WBOX=  538 F  SAMPLE= 1295 F  EXIT1=1521 F  EXIT2=1883 F  EXIT3=1823 F  EXIT4=1894 F  EXIT5=1831 F  EXIT6=1883 F  EXIT7=   0 F  EXIT8=   0 F  EXIT9=1656 F  EXIT10=1625 F  SP(13')= 2289 F  SP(19')= 2219 F  SP(27')= 1662 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR=1625     SORBENT VELOCITY=  15 FT/SEC     SORBENT AIR FLOW=  235  SCFM     [Ca]/[S]=  2.93     J=  53    TEMP INJ(23ft)= 101 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #  10   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  18

 759  15:53:58  82.0   13923    2419   3399   3399   3372   3352      0   16630         2419     687      0           0.17   0.51   1.19               3.5   10.0   15.0   255.0  2280.0
                                                                                       133       0      0                                             0.0   12.0   18.0   306.0  2736.0
 0.0   0.0      87.6             447    671    670    671    667    490                   66       0      0                                             3.0   10.3   15.4   262.3  2345.
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  379 F   MILL OUT=  139 F
T WBOX=  533 F  SAMPLE= 1266 F  EXIT1=1575 F  EXIT2=1839 F  EXIT3=1772 F  EXIT4=1832 F  EXIT5=1801 F  EXIT6=1855 F  EXIT7=   0 F  EXIT8=   0 F  EXIT9=1616 F  EXIT10=1582 F  SP(13')= 2293 F  SP(19')= 2287 F  SP(27')=  324 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0
VALID DATA POINT #  11   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  19

 781  16:09:06  82.8   14063    2454   3364   3307   3378   3349      0   16520         2454     668      0           0.17   0.51   1.17               3.2   40.0   15.6   255.0  1470.
                                                                                       130     105      0                                             0.0   47.2   18.4   300.8  1734.
 0.0   0.0      87.6             441    671    669    671    667    484                   66      44      0                                             3.0   40.4   15.8   257.9  1486.
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.40 in H20   FURNACE P=  0.25 in H20   COAL P=  4.50 in H20   MILL IN=  376 F   MILL OUT=  141 F
T WBOX=  531 F  SAMPLE= 1281 F  EXIT1=1620 F  EXIT2=1821 F  EXIT3=1759 F  EXIT4=1825 F  EXIT5=1798 F  EXIT6=1857 F  EXIT7=   0 F  EXIT8=   0 F  EXIT9=1612 F  EXIT10=1570 F  SP(13')= 2284 F  SP(19')= 2278 F  SP(27')= 1576 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR= 553     SORBENT VELOCITY=  44 FT/SEC     SORBENT AIR FLOW=  668  SCFM     [Ca]/[S]=  0.97     J= 215    TEMP INJ(23ft)= 105 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #  12   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE  20
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DATE             :   12-10-85                        NOZ'L.DES.   :   BASELINE
SYSTEM           :   LWS-INS.                        SEC.CONFGN   :   ASP
BURNER           :   XCL-80  MKII                    SPREADER     :   DIFFUSER
FUEL             :   OHIO-PITT8                      OIL  CHECK   :   -1.42
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            LOAD                PRIM  V -2  V -3  V -4  V -5  V -6  TOTAL      PRIM    STA    OFA        PRIM  SEC1  SEC2(TOTAL)     O2    CO    CO2    NO     SO2
PT0  TIME   MBTU/HR   TA                          FLOW SCFM                       FLOW SCFM                    SR (CUM)                         MEASURED
 OIL        CALC      SCFM                                                        TEMP (F)                                                    CORR TO 0% O2
(%)  LOAD   MEAS                                  TEMP (F)                    VELOCITY (FT/SEC)                                               CORR TO 3% O2
--------------------------------------------------------------------------------------------------------------------------------

802 16:25:56  83.3  14137       2422  3375  3340  3350  3363     0  16517      2422    668     0         0.17  0.50  1.17            3.1   45.0  15.4  255.0  2460.0
                                                                               134      0     0                                      0.0   52.8  18.1  299.2  2886.0
 0.0   0.0    87.6               444   668   665   667   665   488               66      0     0                                      3.0   45.3  15.5  256.4  2473.7
KTRON= 7100  SLEEVE 01 =  3.00 in  SLEEVE 02 = -6.50 in  OUT REG= 40 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  4.40 in H2O  FURNACE P=  0.25 in H2O  COAL P=  4.50 in H2O  MILL IN=  378 F  MILL OUT=  141 F
T WBOX=  519 F  SAMPLE= 1293 F  EXIT1=1786 F  EXIT2= 143 F  EXIT3=1790 F  EXIT4= 225 F  EXIT5=1825 F  EXIT6=1878 F  EXIT7=   0 F  EXIT8=   0 F  EXIT9=1641 F  EXIT10=1630 F  SP(13')= 2324 F  SP(19')= 2309 F  SP(27')= 1750 F
SORBENT LBS/HR=   0    SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT 0  13   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  21
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DATE       :   12-13-85                       NOZ'L.DES.    :   BASELINE
SYSTEM     :   LWS-INS.                       SEC.CONFGN    :   ASP
BURNER     :   XCL-80  MKB                    SPREADER      :   DIFFUSER
FUEL       :   OHIO-PITT8                     OIL  CHECK    :   -0.47
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              LOAD             PRIM  V -2  V -3  V -4  V -5  V -6  TOTAL       PRIM     STA   OFA          PRIM  SFC1  SEC2(TOTAL)        O2    CO    CO2     NO     SO2
PT#   TIME   MBTU/HR    TA                         FLOW SCFM                      FLOW SCFM                       SR (CUM)                               MEASURED
 OIL          CALC     SCFM                                                        TEMP (F)                                                            CORR TO 0% O2
(%)   LOAD    MEAS                                 TEMP (F)                     VELOCITY (FT/SEC)                                                      CORR TO 3% O2
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 336  10:26:43  79.3   13460    2363  3419  3425  3451  3419     0  16077       2363      0     0          0.18  0.48  1.19               3.5   20.0  15.0  270.0 2460.0
                                                                                 142      0     0                                         0.0   24.0  18.0  324.0 2952.0
  0.0   0.0     88.9             472   592   589   580   588   439                65      0     0                                         3.0   20.6  15.4  277.7 2530.3
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  OUT REG= 40 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.50 in H2O  FURNACE P= 0.25 in H2O  COAL P= 4.50 in H2O  MILL IN= 401 F  MILL OUT= 151 F
T WBOX= 490 F  SAMPLE= 1236 F  EXIT1=1812 F  EXIT2=1838 F  EXIT3=1797 F  EXIT4=1853 F  EXIT5=1807 F  EXIT6=1835 F  EXIT7=1571 F  EXIT8=1578 F  EXIT9=1549 F  EXIT10=1408 F  SP(13')= 2182 F  SP(19')= 2128 F  SP(27')= 1788 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=  0 SCFM    (Ca)/(S)= 0.00    J=  0    BASELINE FULL LOAD
VALID DATA POINT #  1  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 23

 632  15:21:50  77.7   13192    2331  3235  3130  3199  3241     0  15756       2331    620     0          0.18  0.51  1.19               3.5   30.0  15.2  230.0 2400.0
                                                                                 147      0     0                                         0.0   36.0  18.2  276.0 2880.0
  0.0   0.0     82.7             444   611   610   609   606   404                65      0     0                                         3.0   30.9  15.6  236.6 2468.6
KTRON= 6700  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  OUT REG= 40 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.20 in H2O  FURNACE P= 0.27 in H2O  COAL P= 4.50 in H2O  MILL IN= 383 F  MILL OUT= 160 F
T WBOX= 510 F  SAMPLE= 1226 F  EXIT1=1764 F  EXIT2=1815 F  EXIT3=1734 F  EXIT4=1811 F  EXIT5=1787 F  EXIT6=1801 F  EXIT7=1530 F  EXIT8=1551 F  EXIT9=1517 F  EXIT10=1379 F  SP(13')= 2216 F  SP(19')= 2081 F  SP(27')= 1732 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=  0 SCFM    (Ca)/(S)= 0.00    J=  0    BASELINE
VALID DATA POINT #  2  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 24

 680  15:37:59  77.8   13207    2311  3221  3183  3181  3256     0  15774       2311    623     0          0.17  0.51  1.19               3.5   30.0  15.0  240.0  636.4
                                                                                 145    101     0                                         0.0   36.0  18.0  288.0  763.7
  0.0   0.0     82.7             467   611   610   609   607   411                64     41     0                                         3.0   30.9  15.4  246.9  654.6
KTRON= 6700  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  OUT REG= 40 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.20 in H2O  FURNACE P= 0.27 in H2O  COAL P= 4.50 in H2O  MILL IN= 403 F  MILL OUT= 158 F
T WBOX= 520 F  SAMPLE= 1192 F  EXIT1=1770 F  EXIT2=1813 F  EXIT3=1759 F  EXIT4=1826 F  EXIT5=1784 F  EXIT6=1810 F  EXIT7=1551 F  EXIT8=1562 F  EXIT9=1531 F  EXIT10=1385 F  SP(13')= 2216 F  SP(19')= 2067 F  SP(27')= 1719 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR=1059    SORBENT VELOCITY= 41 FT/SEC    SORBENT AIR FLOW= 623 SCFM    (Ca)/(S)= 1.98    J= 212    TEMP INJ(23ft)= 101 F     LINWOOD AT 23FT LEVEL
VALID DATA POINT #  3  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 20

 703  16:20:45  77.1   13094    2293  3245  3136  3208  3270     0  15727       2293    575     0          0.18  0.51  1.20               3.6   25.0  15.2  230.0 2280.0
                                                                                 146      0     0                                         0.0   30.2  18.3  277.6 2751.7
  0.0   0.0     85.2             475   610   608   606   607   424                64      0     0                                         3.0   25.9  15.7  237.9 2358.6
KTRON= 6900  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  OUT REG= 40 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.20 in H2O  FURNACE P= 0.27 in H2O  COAL P= 4.50 in H2O  MILL IN= 410 F  MILL OUT= 158 F
T WBOX= 521 F  SAMPLE= 1266 F  EXIT1=1799 F  EXIT2=1839 F  EXIT3=1792 F  EXIT4=1846 F  EXIT5=1813 F  EXIT6=1841 F  EXIT7=1586 F  EXIT8=1608 F  EXIT9=1588 F  EXIT10=1441 F  SP(13')= 2259 F  SP(19')= 2188 F  SP(27')= 1756 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=  0 SCFM    (Ca)/(S)= 0.00    J=  0    BASELINE
VALID DATA POINT #  4  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 26

 710  16:30:54  77.6   13179    2316  3255  3138  3227  3318     0  15829       2316    575     0          0.18  0.51  1.20               3.6   30.0  14.6  240.0  420.0
                                                                                 143     87     0                                         0.0   36.2  17.6  289.7  506.9
  0.0   0.0     85.2             476   611   608   607   608   432                64     37     0                                         3.0   31.0  15.1  248.3  434.5
KTRON= 6900  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  OUT REG= 40 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.20 in H2O  FURNACE P= 0.27 in H2O  COAL P= 4.50 in H2O  MILL IN= 412 F  MILL OUT= 154 F
T WBOX= 519 F  SAMPLE= 1293 F  EXIT1=1785 F  EXIT2=1852 F  EXIT3=1770 F  EXIT4=1853 F  EXIT5=1782 F  EXIT6=1841 F  EXIT7=1614 F  EXIT8=1606 F  EXIT9=1604 F  EXIT10=1466 F  SP(13')= 2251 F  SP(19')= 2193 F  SP(27')= 1745 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR=1778    SORBENT VELOCITY= 37 FT/SEC    SORBENT AIR FLOW= 575 SCFM    (Ca)/(S)= 3.33    J= 208    TEMP INJ(23ft)=  87 F     LINWOOD AT 23FT LEVEL
VALID DATA POINT #  5  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 27
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DATE               :    01-10-86                        NOZ'L.DES.     :    BASELINE
SYSTEM             :    LWS-INS.                        SEC.CONFGN     :    ASP
BURNER             :    XCL-80  MKB                     SPREADER       :    IMPELLER
FUEL               :    OHIO-PITT8                      OIL  CHECK     :    -3.12
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               LOAD            PRIM   V -2   V -3   V -4   V -5   V -6   TOTAL       PRIM     STA     OFA          PRIM   SEC1   SEC2(TOTAL)      O2    CO    CO2      NO     SO2
PT#   TIME   MBTU/HR    TA                          FLOW SCFM                               FLOW SCFM                      SR (CUM)                             MEASURED
  OIL         CALC     SCFM                                                                 TEMP (F)                                                         CORR TO 0% O2
(%)   LOAD    MEAS                                  TEMP (F)                            VELOCITY (FT/SEC)                                                    CORR TO 3% O2
---------------------------------------------------------------------------------------------------------------------------------------------------------

466  13:06:05  79.2   13443     2250   3400   3250   3410   3535      0   16056       2250     195      0          0.17   0.49   1.19            3.5   15.0   15.0   400.0  2310.0
                                                                                     140       0      0                                          0.0   18.0   18.0   480.0  2772.0
 0.0   0.0     86.4              389    616    612    611    612    460                63       0      0                                          3.0   15.4   15.4   411.4  2376.0
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  140 F
T WBOX=  463 F  SAMPLE= 1178 F  EXIT1=1787 F  EXIT2=1013 F  EXIT3=1771 F  EXIT4=1806 F  EXIT5=1745 F  EXIT6=1813 F  EXIT7=1619 F  EXIT8=1547 F  EXIT9=1579 F  EXIT10=1432 F  SP(13')= 2317 F  SP(19')= 2044 F  SP(27')= 1832 F
SORBENT LBS/HR=   0      SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE FULL LOAD
VALID DATA POINT #   1   ELAPSED TIME, MIN   8   RECORD ON TRK   0   FILE  31

515  13:39:32  78.7   13352     2310   3250   3120   3321   3367      0   15947       2310     563      0          0.17   0.51   1.19            3.5   15.0   12.2   360.0  1530.0
                                                                                     148     100      0                                          0.0   18.0   14.6   432.0  1836.0
 0.0   0.0     87.6              384    619    614    614    614    466                65      37      0                                          3.0   15.4   12.5   370.3  1573.7
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  150 F
T WBOX=  475 F  SAMPLE= 1196 F  EXIT1=1775 F  EXIT2=1838 F  EXIT3=1741 F  EXIT4=1807 F  EXIT5=1736 F  EXIT6=1791 F  EXIT7=1608 F  EXIT8=1554 F  EXIT9=1589 F  EXIT10=1438 F  SP(13')= 2338 F  SP(19')= 2119 F  SP(27')= 1814 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR= 613     SORBENT VELOCITY=  37 FT/SEC     SORBENT AIR FLOW=  563  SCFM     [Ca]/[S]=  1.13     J= 157    TEMP INJ(23ft)= 100 F        LINWOOD  AT 23FT LEVEL
VALID DATA POINT #   2   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE  32

523  13:52:36  78.9   13398     2280   3308   3167   3349   3427      0   16092       2280     563      0          0.17   0.51   1.20            3.6   15.0   14.8   370.0  2305.8
                                                                                     147       0      0                                          0.0   18.1   17.9   446.6  2782.9
 0.0   0.0     87.6              386    618    613    612    613    467                63       0      0                                          3.0   15.5   15.3   382.8  2305.3
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  146 F
T WBOX=  473 F  SAMPLE= 1195 F  EXIT1=1701 F  EXIT2=1820 F  EXIT3=1726 F  EXIT4=1799 F  EXIT5=1773 F  EXIT6=1823 F  EXIT7=1559 F  EXIT8=1584 F  EXIT9=1583 F  EXIT10=1432 F  SP(13')= 2366 F  SP(19')= 2139 F  SP(27')= 1779 F
SORBENT LBS/HR=   0      SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   3   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  33

550  14:09:11  78.9   13401     2280   3282   3142   3347   3446      0   16006       2280     508      0          0.17   0.50   1.19            3.5   17.0   14.0   370.0  1029.6
                                                                                     148      99      0                                          0.0   20.4   16.8   444.0  1235.5
 0.0   0.0     87.6              383    618    614    614    614    468                63      33      0                                          3.0   17.5   14.4   380.6  1059.0
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  150 F
T WBOX=  476 F  SAMPLE= 1219 F  EXIT1=1742 F  EXIT2=1837 F  EXIT3=1743 F  EXIT4=1821 F  EXIT5=1759 F  EXIT6=1821 F  EXIT7=1606 F  EXIT8=1602 F  EXIT9=1598 F  EXIT10=1464 F  SP(13')= 2380 F  SP(19')= 2153 F  SP(27')= 1811 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR=1247     SORBENT VELOCITY=  33 FT/SEC     SORBENT AIR FLOW=  508  SCFM     [Ca]/[S]=  2.30     J= 155    TEMP INJ(23ft)=  99 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #   4   ELAPSED TIME, MIN   6   RECORD ON TRK   0   FILE  34

574  14:29:31  78.6   13345     2292   3328   3156   3313   3431      0   16028       2292     508      0          0.17   0.51   1.20            3.6   20.0   14.8   340.0  2400.0
                                                                                     151       0      0                                          0.0   24.1   17.9   458.6  2896.6
 0.0   0.0     87.6              383    619    614    614    614    470                64       0      0                                          3.0   20.7   15.3   393.1  2482.8
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  154 F
T WBOX=  457 F  SAMPLE= 1226 F  EXIT1=1769 F  EXIT2=1852 F  EXIT3=1749 F  EXIT4=1816 F  EXIT5=1759 F  EXIT6=1816 F  EXIT7=1627 F  EXIT8=1591 F  EXIT9=1611 F  EXIT10=1469 F  SP(13')= 2333 F  SP(19')= 2178 F  SP(27')= 1841 F
SORBENT LBS/HR=   0      SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   5   ELAPSED TIME, MIN   3   RECORD ON TRK   0   FILE  35

591  14:42:32  83.3   14140     2275   3268   3156   3355   3390      0   15913       2275     469      0          0.16   0.47   1.13            2.4   30.0   15.6   390.0   988.0
                                                                                     148      99      0                                          0.0   33.9   17.6   440.3  1115.5
 0.0   0.0     87.6              387    620    616    615    615    460                63      31      0                                          3.0   29.0   15.1   377.4   956.1
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  151 F
T WBOX=  467 F  SAMPLE= 1257 F  EXIT1=1789 F  EXIT2=1865 F  EXIT3=1764 F  EXIT4=1846 F  EXIT5=1776 F  EXIT6=1839 F  EXIT7=1655 F  EXIT8=1617 F  EXIT9=1616 F  EXIT10=1485 F  SP(13')= 2367 F  SP(19')= 2108 F  SP(27')= 1868 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR=1807     SORBENT VELOCITY=  31 FT/SEC     SORBENT AIR FLOW=  469  SCFM     [Ca]/[S]=  3.15     J= 157    TEMP INJ(23ft)=  99 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #   6   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE  36
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DATE          :    01-10-86                           NOZ'L.DES.    :    BASELINE
SYSTEM        :    LWS-INS.                           SEC.CONFGN    :    ASP
BURNER        :    XCL-80  MKB                        SPREADER      :    IMPELLER
FUEL          :    OHIO-PITT8                         OIL  CHECK    :    -3,12

           LOAD              PRIM   V -2   V -3   V -4   V -5   V -6   TOTAL        PRIM      STA     OFA            PRIM   SEC1   SEC2(TOTAL)        O2     CO     CO2      NO     SO2
PT#  TIME  MBTU/HR   TA                                FLOW SCFM                               FLOW SCFM                          SR (CUM)                                MEASURED
 OIL       CALC     SCFM                                                                        TEMP (F)                                                                CORR TO 0% O2
(%)  LOAD  MEAS                                        TEMP (F)                             VELOCITY (FT/SEC)                                                           CORR TO 3% O2

 630  15:07:46  80.9   13735     2264   3460   3332   3516   3576      0   16404        2264      256   -- 0          0.16   0.49   1.19               3.5   22.0   14.8   410.0  2310.0
                                                                                        147        0      0                                         0.0   26.4   17.8   492.0  2772.0
 0.0   0.0     87.6               386    616    612    611    611    466                  63        0      0                                         3.0   22.6   15.2   421.7  2376.0
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  150 F
T WBOX=  469 F  SAMPLE= 1247 F  EXIT1=1751 F  EXIT2=1850 F  EXIT3=1785 F  EXIT4=1836 F  EXIT5=1769 F  EXIT6=1823 F  EXIT7=1633 F  EXIT8=1617 F  EXIT9=1620 F  EXIT10=1461 F  SP(13')= 2393 F  SP(19')= 2192 F  SP(27')= 1825 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   7   ELAPSED TIME, MIN   3   RECORD ON TRK   0   FILE  37

 657  15:26:25  77.9   13219     2294   3448   3311   3487   3550      0   16336        2294      246      0          0.17   0.51   1.24               4.1   25.0   14.2   420.0  1440.0
                                                                                        150       97      0                                         0.0   31.1   17.6   521.9  1789.3
 0.0   0.0     87.6               384    615    612    610    611    463                  64       32      0                                         3.0   26.6   15.1   447.3  1533.7
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  153 F
T WBOX=  474 F  SAMPLE= 1263 F  EXIT1=1771 F  EXIT2=1848 F  EXIT3=1786 F  EXIT4=1835 F  EXIT5=1745 F  EXIT6=1815 F  EXIT7=1653 F  EXIT8=1610 F  EXIT9=1620 F  EXIT10=1480 F  SP(13')= 2385 F  SP(19')= 2168 F  SP(27')= 1832 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR= 540     SORBENT VELOCITY=  32 FT/SEC     SORBENT AIR FLOW=  246  SCFM     [Ca]/[S]=  1.01     J= 140    TEMP INJ(23ft)=  97 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #   8   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  38

 676  15:48:16  77.6   13179     2307   3391   3262   3473   3540      0   16193        2307      220      0          0.18   0.50   1.23               4.0   25.0   14.4   420.0  2220.0
                                                                                        147        0      0                                         0.0   30.9   17.8   518.8  2742.4
 0.0   0.0     87.6               383    615    612    610    611    467                  64        0      0                                         3.0   26.5   15.2   444.7  2350.6
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  151 F
T WBOX=  464 F  SAMPLE= 1252 F  EXIT1=1768 F  EXIT2=1835 F  EXIT3=1775 F  EXIT4=1821 F  EXIT5=1772 F  EXIT6=1820 F  EXIT7=1641 F  EXIT8=1611 F  EXIT9=1628 F  EXIT10=1482 F  SP(13')= 2315 F  SP(19')= 2166 F  SP(27')= 1839 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   9   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  39

 728  16:22:38  77.9   13220     2308   3406   3261   3476   3556      0   16243        2308      236      0          0.17   0.50   1.23               4.0   22.0   14.4   370.0  1338.0
                                                                                        149       94      0                                         0.0   27.2   17.8   457.1  1652.8
 0.0   0.0     87.6               386    615    611    611    611    466                  64       31      0                                         3.0   23.3   15.2   391.8  1416.7
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  151 F
T WBOX=  466 F  SAMPLE= 1261 F  EXIT1=1772 F  EXIT2=1838 F  EXIT3=1768 F  EXIT4=1825 F  EXIT5=1743 F  EXIT6=1799 F  EXIT7=1639 F  EXIT8=1595 F  EXIT9=1609 F  EXIT10=1478 F  SP(13')= 2344 F  SP(19')= 2146 F  SP(27')= 1834 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR= 597     SORBENT VELOCITY=  31 FT/SEC     SORBENT AIR FLOW=  236  SCFM     [Ca]/[S]=  1.11     J= 133    TEMP INJ(23ft)=  94 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #  10   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  40

 740  16:39:44  78.0   13247     2297   3408   3254   3473   3515      0   16183        2297      236      0          0.17   0.50   1.22               3.9   20.0   14.2   410.0  1020.0
                                                                                        147       93      0                                         0.0   24.6   17.4   503.5  1252.6
 0.0   0.0     87.6               387    614    610    609    610    460                  64       31      0                                         3.0   21.1   14.9   431.6  1073.7
KTRON= 7100   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.22 in H2O   COAL P=  3.50 in H2O   MILL OUT=  151 F
T WBOX=  472 F  SAMPLE= 1278 F  EXIT1=1784 F  EXIT2=1849 F  EXIT3=1782 F  EXIT4=1840 F  EXIT5=1757 F  EXIT6=1815 F  EXIT7=1659 F  EXIT8=1619 F  EXIT9=1633 F  EXIT10=1502 F  SP(13')= 2377 F  SP(19')= 2136 F  SP(27')= 1839 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR=1151     SORBENT VELOCITY=  31 FT/SEC     SORBENT AIR FLOW=  236  SCFM     [Ca]/[S]=  2.14     J= 174    TEMP INJ(23ft)=  93 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #  11   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  41
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DATE          :   01-13-86                                      NOZ'L.DES.   :   BASELINE
SYSTEM        :   LWS-INS.                                      SEC.CONFGN   :   ASP
BURNER        :   XCL-80 MKB                                    SPREADER     :   IMPELLER
FUEL          :   OHIO-PITT8                                    OIL CHECK    :   0.00
----------------------------------------------------------------------------------------------------------------------------------------------------
           LOAD             PRIM   V -2   V -3   V -4   V -5   V -6   TOTAL       PRIM      STA     OFA          PRIM   SEC1  SEC2(TOTAL)     O2    CO     CO2     NO     SO2
PT#  TIME  MBTU/HR   TA                         FLOW SCFM                          FLOW SCFM                         SR (CUM)                           MEASURED
  OIL      CALC      SCFM                                                           TEMP (F)                                                        CORR TO 0% O2
(%)  LOAD  MEAS                                 TEMP (F)                       VELOCITY (FT/SEC)                                                   CORR TO 3% O2
----------------------------------------------------------------------------------------------------------------------------------------------------

232  12:01:27  79.7  13536    2284   3431   3306   3426   3389     0   16077       2284      242      0           0.17   0.49   1.19         3.4    5.0    14.8   420.0  2303.5
                                                                                   146        0      0                                        0.0    6.0    17.7   501.1  2748.5
 0.0  0.0      88.9            350    717    711    711    710   525               63        0      0                                        3.0    5.1    15.1   429.5  2355.9
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.90 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  146 F
T WBOX=  544 F  SAMPLE= 1180 F  EXIT1=1797 F  EXIT2=1860 F  EXIT3=1813 F  EXIT4=1844 F  EXIT5=1790 F  EXIT6=1824 F  EXIT7=1606 F  EXIT8=1568 F  EXIT9=1601 F  EXIT10=1421 F  SP(13')= 2459 F  SP(19')= 2180 F  SP(27')= 1896 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   1   ELAPSED TIME, MIN    5   RECORD ON TRK   0   FILE  42

281  12:35:33  79.0  13409    2302   3434   3319   3448   3427     0   16196       2302      266      0           0.17   0.50   1.21         3.7   15.0    14.2   440.0   879.7
                                                                                   144       96      0                                        0.0   18.2    17.2   534.1  1062.8
 0.0  0.0      88.9            347    722    716    716    714   526               64       35      0                                        3.0   15.6    14.8   457.8   915.3
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.90 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  142 F
T WBOX=  552 F  SAMPLE= 1211 F  EXIT1=1791 F  EXIT2=1872 F  EXIT3=1783 F  EXIT4=1840 F  EXIT5=1741 F  EXIT6=1813 F  EXIT7=1637 F  EXIT8=1577 F  EXIT9=1606 F  EXIT10=1460 F  SP(13')= 2460 F  SP(19')= 2225 F  SP(27')= 1897 F
SORBENT= LINWOOD      23FT. INJECTION      SORBENT LBS/HR=1555      SORBENT VELOCITY=  35 FT/SEC      SORBENT AIR FLOW=  266  SCFM     [Ca]/[S]=  2.86     J= 245     TEMP INJ(23ft)=  96 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #   2   ELAPSED TIME, MIN    5   RECORD ON TRK   0   FILE  43

293  12:49:15  79.2  13450    2323   3406   3317   3426   3424     0   16064       2323      168      0           0.17   0.49   1.19         3.5   32.0    14.6   450.0  2301.1
                                                                                   144        0      0                                        0.0   38.4    17.5   540.0  2761.3
 0.0  0.0      88.9            347    722    717    716    715   529               64        0      0                                        3.0   32.9    15.0   462.9  2366.8
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.90 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  145 F
T WBOX=  557 F  SAMPLE= 1199 F  EXIT1=1804 F  EXIT2=1855 F  EXIT3=1789 F  EXIT4=1834 F  EXIT5=1758 F  EXIT6=1811 F  EXIT7=1645 F  EXIT8=1588 F  EXIT9=1609 F  EXIT10=1465 F  SP(13')=    0 F  SP(19')= 2226 F  SP(27')= 1912 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   3   ELAPSED TIME, MIN    5   RECORD ON TRK   0   FILE  44

403  13:58:25  76.8  13033    2234   3341   3227   3336   3293     0   16014       2234      582      0           0.17   0.52   1.23         4.0   20.0    15.0   420.0  2280.0
                                                                                   145        0      0                                        0.0   24.7    18.5   518.8  2816.5
 0.0  0.0      88.9            352    739    733    733    731   538               62        0      0                                        3.0   21.2    15.9   444.7  2414.1
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.90 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  142 F
T WBOX=  552 F  SAMPLE= 1203 F  EXIT1=1771 F  EXIT2=1843 F  EXIT3=1730 F  EXIT4=1791 F  EXIT5=1716 F  EXIT6=1784 F  EXIT7=1607 F  EXIT8=1567 F  EXIT9=1568 F  EXIT10=1437 F  SP(13')= 2485 F  SP(19')= 2238 F  SP(27')= 1905 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   4   ELAPSED TIME, MIN    5   RECORD ON TRK   0   FILE  45

416  14:07:51  78.1  13252    2231   3308   3150   3294   3258     0   15828       2231      587      0           0.17   0.51   1.19         3.5   22.0    15.2   450.0   457.9
                                                                                   143      101      0                                        0.0   26.4    18.2   540.0   549.5
 0.0  0.0      88.9            354    741    735    735    733   541               62       39      0                                        3.0   22.6    15.6   462.9   471.0
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.90 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  139 F
T WBOX=  563 F  SAMPLE= 1248 F  EXIT1=1809 F  EXIT2=1903 F  EXIT3=1785 F  EXIT4=1852 F  EXIT5=1751 F  EXIT6=1839 F  EXIT7=1650 F  EXIT8=1621 F  EXIT9=1629 F  EXIT10=1491 F  SP(13')= 2350 F  SP(19')= 2254 F  SP(27')= 1909 F
SORBENT= LINWOOD      23FT. INJECTION      SORBENT LBS/HR=1698      SORBENT VELOCITY=  39 FT/SEC      SORBENT AIR FLOW=  587  SCFM     [Ca]/[S]=  3.16     J= 221     TEMP INJ(23ft)= 101 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #   5   ELAPSED TIME, MIN    5   RECORD ON TRK   0   FILE  46

455  14:33:53  78.9  13400    2266   3261   3144   3307   3336     0   15916       2266      603      0           0.17   0.51   1.19         3.4   20.0    15.2   380.0   780.0
                                                                                   144       99      0                                        0.0   23.9    18.1   453.4   930.7
 0.0  0.0      88.9            350    737    731    732    730   536               63       40      0                                        3.0   20.5    15.5   388.6   797.7
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.90 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  143 F
T WBOX=  567 F  SAMPLE= 1257 F  EXIT1=1810 F  EXIT2=1901 F  EXIT3=1793 F  EXIT4=1864 F  EXIT5=1765 F  EXIT6=1846 F  EXIT7=1656 F  EXIT8=1635 F  EXIT9=1646 F  EXIT10=1518 F  SP(13')= 2318 F  SP(19')= 2277 F  SP(27')= 1922 F
SORBENT= LINWOOD      23FT. INJECTION      SORBENT LBS/HR=1118      SORBENT VELOCITY=  40 FT/SEC      SORBENT AIR FLOW=  603  SCFM     [Ca]/[S]=  2.06     J= 201     TEMP INJ(23ft)=  99 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #   6   ELAPSED TIME, MIN    5   RECORD ON TRK   0   FILE  47
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DATE      :  01-13-86                    NOZ'L.DES.   :  BASELINE
SYSTEM    :  LWS-INS.                    SEC.CONFGN   :  ASP
BURNER    :  XCL-80  MKB                 SPREADER     :  IMPELLER
FUEL      :  OHIO-PITT8                  OIL CHECK    :  0.00
-----------------------------------------------------------------------------------------------------------------------------------------------
         LOAD              PRIM  V -2  V -3  V -4  V -5  V -6  TOTAL       PRIM     STA    OFA        PRIM  SEC1  SEC2(TOTAL)    O2   CO   CO2    NO    SO2
PT#  TIME  MBTU/HR   TA                    FLOW SCFM                          FLOW SCFM                    SR (CUM)                            MEASURED
 OIL       CALC     SCFM                                                       TEMP (F)                                                   CORR TO 0% O2
(%)  LOAD  MEAS                            TEMP (F)                      VELOCITY (FT/SEC)                                                 CORR TO 3% O2
-----------------------------------------------------------------------------------------------------------------------------------------------
489 15:00:01  77.7  13185  2271  3306  3147  3338  3309     0  15926       2271     555     0         0.17  0.51  1.21          3.7  23.0  15.2  410.0 2250.0
                                                                            143       0     0                                     0.0  27.9  18.5  497.7 2731.2
 0.0  0.0     88.9          350   730   724   724   723   532               63       0     0                                     3.0  23.9  15.8  426.6 2341.0
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG . IN REG =  30 (CW)DEG  P WBOX= 3.90 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 142 F
T WBOX= 543 F  SAMPLE= 1255 F  EXIT1=1770 F  EXIT2=1868 F  EXIT3=1765 F  EXIT4=1829 F  EXIT5=1762 F  EXIT6=1825 F  EXIT7=1640 F  EXIT8=1624 F  EXIT9=1625 F  EXIT10=1478 F  SP(13')= 2316 F  SP(19')= 2270 F  SP(27')= 1910 F
SORBENT LBS/HR=   0    SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=   0 SCFM    [Ca]/[S]= 0.00    J=   0   BASELINE
VALID DATA POINT #  7  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 48

503 15:09:12  78.6  13339  2238  3317  3190  3360  3276     0  15932       2238     550     0         0.17  0.50  1.19          3.5  27.0  15.4  430.0 1740.0
                                                                            143     102     0                                     0.0  32.4  18.5  516.0 2008.0
 0.0  0.0     88.9          351   730   724   724   723   534               62      36     0                                     3.0  27.8  15.8  442.3 1789.7
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX= 3.90 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 143 F
T WBOX= 540 F  SAMPLE= 1265 F  EXIT1=1803 F  EXIT2=1892 F  EXIT3=1772 F  EXIT4=1843 F  EXIT5=1753 F  EXIT6=1831 F  EXIT7=1655 F  EXIT8=1620 F  EXIT9=1629 F  EXIT10=1509 F  SP(13')= 2327 F  SP(19')= 2314 F  SP(27')= 1942 F
SORBENT= VICRON    23FT. INJECTION    SORBENT LBS/HR= 692    SORBENT VELOCITY= 36 FT/SEC    SORBENT AIR FLOW= 550 SCFM    [Ca]/[S]= 1.04    J= 155    TEMP INJ(23ft)= 102 F    VICRON AT 23FT LEVEL
VALID DATA POINT #  8  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 49

533 15:34:52  78.9  13398  2262  3381  3176  3391  3392     0  16092       2262     490     0         0.17  0.50  1.20          3.6  20.0  15.0  410.0 2400.0
                                                                            143       0     0                                     0.0  24.1  18.1  494.0 2896.6
 0.0  0.0     88.9          349   728   722   723   722   536               62       0     0                                     3.0  20.7  15.5  424.1 2462.8
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX= 3.90 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 143 F
T WBOX= 548 F  SAMPLE= 1234 F  EXIT1=1780 F  EXIT2=1873 F  EXIT3=1766 F  EXIT4=1830 F  EXIT5=1759 F  EXIT6=1828 F  EXIT7=1625 F  EXIT8=1624 F  EXIT9=1627 F  EXIT10=1493 F  SP(13')= 2325 F  SP(19')= 2275 F  SP(27')= 1904 F
SORBENT LBS/HR=   0    SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=   0 SCFM    [Ca]/[S]= 0.00    J=   0   BASELINE
VALID DATA POINT #  9  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 50

557 15:48:54  77.6  13166  2262  3389  3238  3425  3373     0  16177       2262     490     0         0.17  0.51  1.23          4.0  20.0  15.0  410.0 1282.0
                                                                            144     103     0                                     0.0  24.7  18.5  506.5 1583.6
 0.0  0.0     88.9          348   719   714   716   714   534               62      32     0                                     3.0  21.2  15.9  434.1 1357.4
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX= 3.90 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 143 F
T WBOX= 548 F  SAMPLE= 1284 F  EXIT1=1787 F  EXIT2=1870 F  EXIT3=1756 F  EXIT4=1815 F  EXIT5=1736 F  EXIT6=1802 F  EXIT7=1653 F  EXIT8=1615 F  EXIT9=1633 F  EXIT10=1512 F  SP(13')= 2287 F  SP(19')= 2271 F  SP(27')= 1907 F
SORBENT= VICRON    23FT. INJECTION    SORBENT LBS/HR=1458    SORBENT VELOCITY= 32 FT/SEC    SORBENT AIR FLOW= 490 SCFM    [Ca]/[S]= 2.22    J= 156    TEMP INJ(23ft)= 103 F    VICRON AT 23FT LEVEL
VALID DATA POINT # 10  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 51

591 16:19:33  80.7  13705  2269  3448  3337  3496  3471     0  16461       2269     440     0         0.17  0.50  1.20          3.6  15.0  15.2  420.0 1123.9
                                                                            146     102     0                                     0.0  18.1  18.3  506.9 1356.4
 0.0  0.0     88.9          357   713   707   709   708   533               63      29     0                                     3.0  15.5  15.7  434.5 1162.
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX= 3.90 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 147 F
T WBOX= 537 F  SAMPLE= 1327 F  EXIT1=1828 F  EXIT2=1906 F  EXIT3=1793 F  EXIT4=1862 F  EXIT5=1817 F  EXIT6=1876 F  EXIT7=1705 F  EXIT8=1700 F  EXIT9=1689 F  EXIT10=1569 F  SP(13')= 2302 F  SP(19')= 2289 F  SP(27')= 1631 F
SORBENT= VICRON    23FT. INJECTION    SORBENT LBS/HR=2169    SORBENT VELOCITY= 29 FT/SEC    SORBENT AIR FLOW= 440 SCFM    [Ca]/[S]= 3.17    J= 156    TEMP INJ(23ft)= 102 F    VICRON AT 23FT LEVEL
VALID DATA POINT # 11  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 52

608 16:31:01  77.7  13191  2248  3379  3216  3376  3364     0  16024       2248     440     0         0.17  0.51  1.21          3.8  12.0  14.6  430.0 2232.
                                                                            145       0     0                                     0.0  14.7  17.8  525.0 2725.
 0.0  0.0     88.9          358   751   745   745   742   544               62       0     0                                     3.0  12.6  15.3  450.0 2336.
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX= 3.90 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 143 F
T WBOX= 563 F  SAMPLE= 1307 F  EXIT1=1026 F  EXIT2=1910 F  EXIT3=1801 F  EXIT4=1864 F  EXIT5=1805 F  EXIT6=1659 F  EXIT7=1690 F  EXIT8=1671 F  EXIT9=1665 F  EXIT10=1543 F  SP(13')= 2297 F  SP(19')= 2280 F  SP(27')= 1945 F
SORBENT LBS/HR=   0    SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=   0 SCFM    [Ca]/[S]= 0.00    J=   0   BASELINE
VALID DATA POINT # 12  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 53
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DATE        :  01-14-86                  NOZ'L.DES.    :  BASELINE
SYSTEM      :  LWS-INS.                  SEC.CONFGN    :  ASP
BURNER      :  XCL-80 MKII               SPREADER      :  IMPELLER
FUEL        :  OHIO-PITT8                OIL CHECK     :  -1.20
-----------------------------------------------------------------------------------------------------------------------------------
            LOAD          PRIM  V-2   V-3   V-4   V-5   V-6   TOTAL      PRIM    STA    OFA       PRIM  SEC1  SEC2(TOTAL)     O2    CO    CO2    NO    SO
PT#  TIME  MBTU/HR  TA                      FLOW SCFM                     FLOW SCFM                      SR (CUM)                           MEASURED
 OIL        CALC   SCFM                                                   TEMP (F)                                                       CORR TO 0% O2
(%)  LOAD   MEAS                            TEMP (F)                     VELOCITY (FT/SEC)                                              CORR TO 3% O2
-----------------------------------------------------------------------------------------------------------------------------------
295 12:07:55  78.2  13266   2273  3413  3280  3437  3377     0  16024    2273    243     0       0.17  0.50  1.21          3.7   15.0  14.8  430.0 2200.0
                                                                          143      0     0                                   0.0   18.2  18.0  522.0 2767.0
 0.0   0.0    90.1           388   785   770   778   775   564              63      0     0                                   3.0   15.6  15.4  447.4 2372.3
KTRON= 7300  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.00 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 145 F
T WBOX=  584 F  SAMPLE= 1211 F  EXIT1=1782 F  EXIT2=1858 F  EXIT3=1784 F  EXIT4=1833 F  EXIT5=1765 F  EXIT6=1841 F  EXIT7=1602 F  EXIT8=1589 F  EXIT9=1584 F  EXIT10=1486 F  SP(13')= 2230 F  SP(19')= 2197 F  SP(27')= 1860 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=  0 SCFM   [Ca]/[S]= 0.00    J=  0    BASELINE - FULL LOAD
VALID DATA POINT #  1  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE  54

315 12:25:25  79.9  13569   2307  3390  3266  3404  3338     0  15940    2307    227     0       0.17  0.48  1.17          3.2   15.0  15.2  420.0 1560.0
                                                                          143     85     0                                   0.0   17.7  17.9  495.5 1840.4
 0.0   0.0    90.7           390   787   780   781   778   566              64     58     0                                   3.0   15.2  15.4  424.7 1577.5
KTRON= 7350  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.00 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 143 F
T WBOX=  578 F  SAMPLE= 1234 F  EXIT1=1828 F  EXIT2=1894 F  EXIT3=1807 F  EXIT4=1857 F  EXIT5=1770 F  EXIT6=1847 F  EXIT7=1645 F  EXIT8=1611 F  EXIT9=1613 F  EXIT10=1531 F  SP(13')= 2265 F  SP(19')= 2240 F  SP(27')= 1709 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR= 600    SORBENT VELOCITY=  58 FT/SEC    SORBENT AIR FLOW=  227  SCFM   [Ca]/[S]=  1.09    J= 493    TEMP INJ(23ft)=  85 F       LINWOOD AT 23FT LEVEL
VALID DATA POINT #  2  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE  55

343 12:45:26  78.6  13339   2299  3418  3323  3461  3340     0  16021    2299    180     0       0.17  0.49  1.20          3.6   15.0  14.8  420.0 2340.0
                                                                          143      0     0                                   0.0   18.1  17.9  506.9 2824.1
 0.0   0.0    91.3           388   791   785   785   783   569              63      0     0                                   3.0   15.5  15.3  434.5 2420.7
KTRON= 7400  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.00 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 144 F
T WBOX=  582 F  SAMPLE= 1235 F  EXIT1=1790 F  EXIT2=1862 F  EXIT3=1797 F  EXIT4=1835 F  EXIT5=1767 F  EXIT6=1829 F  EXIT7=1621 F  EXIT8=1689 F  EXIT9=1686 F  EXIT10=1543 F  SP(13')= 2251 F  SP(19')= 2206 F  SP(27')= 1832 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=  0 SCFM   [Ca]/[S]= 0.00    J=  0    BASELINE
VALID DATA POINT #  3  ELAPSED TIME, MIN  4  RECORD ON TRK  0  FILE  56

355 12:56:07  81.3  13802   2297  3455  3352  3482  3351     0  16125    2297    187     0       0.17  0.48  1.17          3.1   25.0  15.0  450.0 1200.0
                                                                          143     88     0                                   0.0   29.3  17.6  527.9 1407.8
 0.0   0.0    91.3           387   793   787   787   785   568              63     48     0                                   3.0   25.1  15.1  452.5 1206.7
KTRON= 7400  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.00 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 142 F
T WBOX=  594 F  SAMPLE= 1273 F  EXIT1=1833 F  EXIT2=1904 F  EXIT3=1843 F  EXIT4=1885 F  EXIT5=1801 F  EXIT6=1892 F  EXIT7=1668 F  EXIT8=1655 F  EXIT9=1644 F  EXIT10=1571 F  SP(13')= 2300 F  SP(19')= 2250 F  SP(27')= 1924 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR=1105    SORBENT VELOCITY=  48 FT/SEC    SORBENT AIR FLOW=  187  SCFM   [Ca]/[S]=  1.98    J= 482    TEMP INJ(23ft)=  88 F       LINWOOD AT 23FT LEVEL
VALID DATA POINT #  4  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE  57

405 13:47:14  86.0  14593   2249  3600  3500  3644  3520     0  16685    2249    173     0       0.15  0.46  1.14          2.7   15.0  15.8  420.0 1080.0
                                                                          142     85     0                                   0.0   17.2  18.1  482.0 1239.3
 0.0   0.0    91.3           389   787   781   782   779   567              62     45     0                                   3.0   14.8  15.5  413.1 1062.3
KTRON= 7400  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.00 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 145 F
T WBOX=  577 F  SAMPLE= 1333 F  EXIT1=1844 F  EXIT2=1927 F  EXIT3=1853 F  EXIT4=1895 F  EXIT5=1818 F  EXIT6=1880 F  EXIT7=1692 F  EXIT8=1691 F  EXIT9=1686 F  EXIT10=1590 F  SP(13')= 2315 F  SP(19')= 2271 F  SP(27')= 1950 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR=1686    SORBENT VELOCITY=  45 FT/SEC    SORBENT AIR FLOW=  173  SCFM   [Ca]/[S]=  2.85    J= 554    TEMP INJ(23ft)=  85 F       LINWOOD AT 23FT LEVEL
VALID DATA POINT #  5  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE  58

437 14:10:40  80.1  13600   2246  3444  3367  3491  3347     0  16243    2246    350     0       0.17  0.49  1.19          3.5   20.0  14.6  390.0 2280.0
                                                                          144      0     0                                   0.0   24.0  17.5  468.0 2736.0
 0.0   0.0    86.4           389   790   783   785   781   573              62      0     0                                   3.0   20.6  15.0  401.1 2345.1
KTRON= 7000  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0 in  OUT REG= 50 (CW)DEG  IN REG = 30 (CW)DEG  P WBOX= 4.00 in H2O  FURNACE P= 0.18 in H2O  COAL P= 3.50 in H2O  MILL OUT= 151 F
T WBOX=  587 F  SAMPLE= 1297 F  EXIT1=1795 F  EXIT2=1896 F  EXIT3=1788 F  EXIT4=1836 F  EXIT5=1765 F  EXIT6=1836 F  EXIT7=1649 F  EXIT8=1635 F  EXIT9=1620 F  EXIT10=1546 F  SP(13')= 2291 F  SP(19')= 2277 F  SP(27')= 1914 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=  0 SCFM   [Ca]/[S]= 0.00    J=  0    BASELINE
VALID DATA POINT #  6  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE  59
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DATE         :   01-14-86                 NOZ'L.DES.   :   BASELINE
SYSTEM       :   LWS-INS.                 SEC.CONFGN   :   ASP
BURNER       :   XCL-80 MKB               SPREADER     :   IMPELLER
FUEL         :   OHIO-PITT8               OIL CHECK    :   -1,20

            LOAD               PRIM  V -2  V -3  V -4  V -5  V -6  TOTAL        PRIM     STA    OFA          PRIM  SFC1  SFC2(TOTAL)        O2    CO    CO2     NO     SO2
PT#   TIME  MBTU/HR   TA                         FLOW SCFM                          FLOW SCFM                       SR (CUM)                                MEASURED
 OIL        CALC      SCFM                                                           TEMP (F)                                                            CORR TO 0% O2
(%)   LOAD  MEAS                                 TEMP (F)                        VELOCITY (FT/SEC)                                                       CORR TO 3% O2

 457  14:25:15  82.3  13971    2287  3443  3295  3467  3399     0  16234        2287     343     0           0.16  0.48  1.16              3.0   30.0  15.6  400.0  1500.0
                                                                                 146      87     0                                          0.0   35.0  18.2  466.7  1750.0
 0.0  0.0       86.4            401   790   783   783   782   575                 63      89     0                                          3.0   30.0  15.6  400.0  1500.0
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =  0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.00 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  149 F
T WBOX=  572 F  SAMPLE= 1319 F  EXIT1=1834 F  EXIT2=1929 F  EXIT3=1821 F  EXIT4=1877 F  EXIT5=1791 F  EXIT6=1869 F  EXIT7=1674 F  EXIT8=1658 F  EXIT9=1655 F  EXIT10=1504 F  SP(13')= 2315 F  SP(19')= 2296 F  SP(27')= 1936 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR= 481    SORBENT VELOCITY=  89 FT/SEC    SORBENT AIR FLOW=  343  SCFM    [Ca]/[S]=  0.85    J= 948    TEMP INJ(23ft)=  87 F       LINWOOD AT 23FT LEVEL
VALID DATA POINT #   7   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE  60

 476  14:43:49  77.8  13207    2233  3449  3306  3459  3392     0  16134        2233     295     0           0.17  0.50  1.22              3.9   25.0  15.0  400.0  2370.0
                                                                                 150       0     0                                          0.0   30.7  18.4  491.2  2910.5
 0.0  0.0       86.4            408   614   612   613   616   486                 62       0     0                                          3.0   26.3  15.8  421.1  2494.7
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =  0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.00 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  159 F
T WBOX=  479 F  SAMPLE= 1263 F  EXIT1=1779 F  EXIT2=1873 F  EXIT3=1780 F  EXIT4=1824 F  EXIT5=1745 F  EXIT6=1823 F  EXIT7=1635 F  EXIT8=1632 F  EXIT9=1625 F  EXIT10=1555 F  SP(13')= 2260 F  SP(19')= 2233 F  SP(27')= 1891 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   8   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  61

 489  14:52:58  80.8  13712    2234  3510  3322  3531  3465     0  16377        2234     316     0           0.16  0.49  1.19              3.5   28.0  15.2  380.0   900.0
                                                                                 150      84     0                                          0.0   33.6  18.2  456.0  1080.0
 0.0  0.0       86.4            406   567   566   568   569   446                 62      81     0                                          3.0   28.8  15.6  390.9   925.7
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =  0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.00 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  156 F
T WBOX=  444 F  SAMPLE= 1323 F  EXIT1=1802 F  EXIT2=1887 F  EXIT3=1792 F  EXIT4=1848 F  EXIT5=1752 F  EXIT6=1829 F  EXIT7=1653 F  EXIT8=1641 F  EXIT9=1644 F  EXIT10=1551 F  SP(13')= 2268 F  SP(19')= 2247 F  SP(27')= 1902 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR=1059    SORBENT VELOCITY=  81 FT/SEC    SORBENT AIR FLOW=  316  SCFM    [Ca]/[S]=  1.91    J=1041    TEMP INJ(23ft)=  84 F       LINWOOD AT 23FT LEVEL
VALID DATA POINT #   9   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  62

 522  15:17:36  80.1  13591    2235  3445  3303  3438  3357     0  16053        2235     275     0           0.16  0.48  1.18              3.3   20.0  15.2  390.0  2280.0
                                                                                 151       0     0                                          0.0   23.7  18.0  462.7  2705.1
 0.0  0.0       86.4            403   612   609   609   607   462                 62       0     0                                          3.0   20.3  15.5  396.6  2318.6
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =  0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.00 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  158 F
T WBOX=  463 F  SAMPLE= 1299 F  EXIT1=1787 F  EXIT2=1380 F  EXIT3=1781 F  EXIT4=1830 F  EXIT5=1754 F  EXIT6=1823 F  EXIT7=1633 F  EXIT8=1633 F  EXIT9=1633 F  EXIT10=1532 F  SP(13')= 2264 F  SP(19')= 2245 F  SP(27')= 1894 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #  10   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  63

 547  15:34:10  80.3  13625    2251  3542  3395  3577  3416     0  16457        2251     276     0           0.17  0.49  1.21              3.7   10.0  15.0  440.0   570.0
                                                                                 151      85     0                                          0.0   12.1  18.2  534.1   691.9
 0.0  0.0       86.4            403   614   610   610   608   460                 63      71     0                                          3.0   10.4  15.6  457.8   593.1
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =  0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.00 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  161 F
T WBOX=  462 F  SAMPLE= 1339 F  EXIT1=1785 F  EXIT2=1882 F  EXIT3=1779 F  EXIT4=1844 F  EXIT5=1772 F  EXIT6=1842 F  EXIT7=1650 F  EXIT8=1661 F  EXIT9=1656 F  EXIT10=1561 F  SP(13')= 2270 F  SP(19')= 2267 F  SP(27')= 1882 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR=1698    SORBENT VELOCITY=  71 FT/SEC    SORBENT AIR FLOW=  276  SCFM    [Ca]/[S]=  3.08    J=1064    TEMP INJ(23ft)=  85 F       LINWOOD AT 23FT LEVEL
VALID DATA POINT #  11   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  64

 572  15:52:45  79.4  13482    2254  3500  3362  3558  3427     0  16377        2254     276     0           0.17  0.50  1.21              3.8   23.0  15.0  420.0  2280.0
                                                                                 148       0     0                                          0.0   28.1  18.3  512.8  2783.7
 0.0  0.0       86.4            409   616   611   614   609   445                 63       0     0                                          3.0   24.1  15.7  439.5  2386.0
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =  0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.00 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  159 F
T WBOX=  463 F  SAMPLE= 1325 F  EXIT1=1793 F  EXIT2=1872 F  EXIT3=1788 F  EXIT4=1833 F  EXIT5=1763 F  EXIT6=1820 F  EXIT7=1650 F  EXIT8=1648 F  EXIT9=1649 F  EXIT10=1549 F  SP(13')= 2246 F  SP(19')= 2225 F  SP(27')= 1896 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #  12   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  65
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DATE        :   01-15-86                          NOZ'L.DES.   :   BASELINE
SYSTEM      :   LWS-INS.                          SEC.CONFGN   :   ASP
BURNER      :   XCL-80  MKB                       SPREADER     :   IMPELLER
FUEL        :   OHIO-PITT8                        OIL  CHECK   :   0.24
_____________________________________________________________________________________________________________________________________
               LOAD            PRIM   V -2   V -3   V -4   V -5   V -6   TOTAL        PRIM      STA    OFA         PRIM   SEC1   SEC2(TOTAL)      O2    CO    CO2     NO     SO2
PT#   TIME   MBTU/HR    TA                          FLOW SCFM                            FLOW SCFM                            SR (CUM)                              MEASURED
  OIL          CALC    SCFM                                                               TEMP (F)                                                              CORR TO 0% O2
(%)   LOAD     MEAS                                 TEMP (F)                         VELOCITY (FT/SEC)                                                          CORR TO 3% O2
_____________________________________________________________________________________________________________________________________

 290  11:36:06   79.8   13550     2320   3445   3417   3378   3369      0   16183        2320      254      0        0.17   0.49   1.19             3.5   25.0   15.2  340.0  2460.0
                                                                                         141        0      0                                         0.0   30.0   18.2  408.0  2952.0
  0.0   0.0      85.2              377    628    622    621    620    465                 64        0      0                                         3.0   25.7   15.6  349.7  2530.3
KTRON= 6900   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  147 F
T WBOX= 1268 F  SAMPLE= 1234 F  EXIT1=1797 F  EXIT2=1830 F  EXIT3=1771 F  EXIT4=1812 F  EXIT5=1722 F  EXIT6=1792 F  EXIT7=1594 F  EXIT8=1572 F  EXIT9=1579 F  EXIT10=1445 F  SP(13')= 2132 F  SP(19')= 2070 F  SP(27')= 1055 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #  1   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  66

 321  11:57:29   80.9   13734     2347   3422   3436   3376   3386      0   16222        2347      254      0        0.17   0.49   1.18             3.3   50.0   15.0  370.0  1320.0
                                                                                         143       84      0                                         0.0   59.1   17.8  439.0  1566.1
  0.0   0.0      85.2              382    625    620    620    617    462                 65       32      0                                         3.0   50.8   15.3  376.3  1342.4
KTRON= 6900   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  152 F
T WBOX= 1009 F  SAMPLE= 1257 F  EXIT1=1794 F  EXIT2=1836 F  EXIT3=1783 F  EXIT4=1821 F  EXIT5=1713 F  EXIT6=1797 F  EXIT7=1612 F  EXIT8=1576 F  EXIT9=1595 F  EXIT10=1463 F  SP(13')= 2149 F  SP(19')= 2099 F  SP(27')= 1865 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR= 984     SORBENT VELOCITY=  32 FT/SEC     SORBENT AIR FLOW=  254  SCFM     [Ca]/[S]=  1.77     J= 177     TEMP INJ(23ft)=  84 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #  2   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE  67

 347  12:17:34   78.9   13386     2305   3435   3453   3380   3378      0   16168        2305      218      0        0.17   0.49   1.21             3.7   45.0   15.0  380.0  2310.0
                                                                                         144        0      0                                         0.0   54.6   18.2  461.3  2804.0
  0.0   0.0      85.2              385    624    621    620    615    445                 64        0      0                                         3.0   46.8   15.6  395.4  2403.5
KTRON= 6900   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  149 F
T WBOX= 1210 F  SAMPLE= 1245 F  EXIT1=1775 F  EXIT2=1823 F  EXIT3=1790 F  EXIT4=1807 F  EXIT5=1719 F  EXIT6=1790 F  EXIT7=1607 F  EXIT8=1579 F  EXIT9=1599 F  EXIT10=1446 F  SP(13')= 2134 F  SP(19')= 2086 F  SP(27')= 1842 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #  3   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  68

 367  12:31:10   79.3   13465     2300   3464   3410   3391   3390      0   16173        2300      218      0        0.17   0.49   1.20             3.6   30.0   15.0  380.0  1140.0
                                                                                         147       89      0                                         0.0   36.2   18.1  458.6  1375.9
  0.0   0.0      85.2              385    624    620    619    615    452                 64       28      0                                         3.0   31.0   15.5  393.1  1179.3
KTRON= 6900   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  153 F
T WBOX= 1479 F  SAMPLE= 1250 F  EXIT1=1778 F  EXIT2=1829 F  EXIT3=1780 F  EXIT4=1810 F  EXIT5=1726 F  EXIT6=1788 F  EXIT7=1617 F  EXIT8=1589 F  EXIT9=1611 F  EXIT10=1459 F  SP(13')= 2148 F  SP(19')= 2090 F  SP(27')= 1853 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR=1034     SORBENT VELOCITY=  28 FT/SEC     SORBENT AIR FLOW=  218  SCFM     [Ca]/[S]=  1.89     J= 145     TEMP INJ(23ft)=  89 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #  4   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  69

 394  12:55:13   78.6   13346     2341   3443   3427   3444   3363      0   16212        2341      194      0        0.18   0.50   1.21             3.8   45.0   14.8  390.0  1200.0
                                                                                         148       89      0                                         0.0   54.9   18.1  476.2  1465.1
  0.0   0.0      85.2              392    624    620    618    615    465                 65       25      0                                         3.0   47.1   15.5  408.1  1255.8
KTRON= 6900   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  153 F
T WBOX= 1287 F  SAMPLE= 1281 F  EXIT1=1804 F  EXIT2=1854 F  EXIT3=1821 F  EXIT4=1846 F  EXIT5=1762 F  EXIT6=1831 F  EXIT7=1642 F  EXIT8=1634 F  EXIT9=1640 F  EXIT10=1484 F  SP(13')= 2176 F  SP(19')= 2081 F  SP(27')= 1871 F
SORBENT= LINWOOD     23FT. INJECTION     SORBENT LBS/HR=1462     SORBENT VELOCITY=  25 FT/SEC     SORBENT AIR FLOW=  194  SCFM     [Ca]/[S]=  2.70     J= 148     TEMP INJ(23ft)=  89 F        LINWOOD AT 23FT LEVEL
VALID DATA POINT #  5   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  70

 400  13:05:26   79.1   13423     2337   3387   3376   3361   3371      0   16032        2337      200      0        0.17   0.49   1.19             3.5   55.0   15.0  390.0  2400.0
                                                                                         147        0      0                                         0.0   66.0   18.0  468.0  2880.0
  0.0   0.0      85.2              369    625    621    620    616    462                 65        0      0                                         3.0   56.6   15.4  401.1  2468.6
KTRON= 6900   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  151 F
T WBOX= 1216 F  SAMPLE= 1275 F  EXIT1=1796 F  EXIT2=1848 F  EXIT3=1813 F  EXIT4=1830 F  EXIT5=1750 F  EXIT6=1819 F  EXIT7=1635 F  EXIT8=1632 F  EXIT9=1645 F  EXIT10=1493 F  SP(13')= 2158 F  SP(19')= 2094 F  SP(27')= 1868 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #  6   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  71
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DATE          :   01-15-86                       NOZ'L.DES.     :   BASELINE
SYSTEM        :   LWS-INS.                       SEC.CONFGN     :   ASP
BURNER        :   XCL-80  MKII                   SPREADER       :   IMPELLER
FUEL          :   OHIO-PITT8                     OIL  CHECK     :   0.24
--------------------------------------------------------------------------------------------------------------------------------
              LOAD              PRIM   V-2   V-3   V-4   V-5   V-6   TOTAL       PRIM     STA    OFA      PRIM   SEC1  SEC2(TOTAL)      O2     CO     CO2     NO     S
PT#   TIME   MBTU/HR    TA                         FLOW SCFM                         FLOW SCFM                     SR (CUM)                          MEASURED
  OIL          CALC     SCFM                                                          TEMP (F)                                                       CORR TO 0% O2
(%)   LOAD     MEAS                                TEMP (F)                       VELOCITY (FT/SEC)                                                  CORR TO 3% O2
--------------------------------------------------------------------------------------------------------------------------------

423  13:16:26   81.2   13777    2328   3449  3485  3484  3486    0   16273       2328     200     0       0.17   0.48   1.18         3.3    35.0   15.2   390.0  1140.
                                                                                  147      87     0                                    0.0    41.5   18.0   462.7  1352.
 0.0   0.0      85.2             391    623   620   619   615   463               65      26     0                                    3.0    35.6   15.5   396.6  1159.
KTRON= 6900  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.60 in H2O  FURNACE P=  0.18 in H2O  COAL P=  3.50 in H2O  MILL OUT=  155 F
T WBOX= 1618 F  SAMPLE= 1289 F  EXIT1=1783 F  EXIT2=1849 F  EXIT3=1780 F  EXIT4=1818 F  EXIT5=1743 F  EXIT6=1805 F  EXIT7=1626 F  EXIT8=1621 F  EXIT9=1620 F  EXIT10=1484 F  SP(13')= 2166 F  SP(19')= 2095 F  SP(27')= 1865 F
SORBENT= LINWOOD    23FT. INJECTION    SORBENT LBS/HR=1663    SORBENT VELOCITY=  26 FT/SEC    SORBENT AIR FLOW=  200  SCFM    [Ca]/[S]=  2.98    J= 166    TEMP INJ(23ft)=  87 F    LINWOOD AT 23FT LEVEL
VALID DATA POINT #   7   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  72

469  13:40:20   80.1   13598    2286   3479  3487  3427  3434    0   16333       2286     218     0       0.17   0.49   1.20         3.6    30.0   15.0   380.0  2430.
                                                                                  147       0     0                                    0.0    36.2   18.1   458.6  2932.
 0.0   0.0      85.2             397    623   618   618   615   452               63       0     0                                    3.0    31.0   15.5   393.1  2513.
KTRON= 6900  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.60 in H2O  FURNACE P=  0.18 in H2O  COAL P=  3.50 in H2O  MILL OUT=  152 F
T WBOX= 1246 F  SAMPLE= 1282 F  EXIT1=1764 F  EXIT2=1835 F  EXIT3=1757 F  EXIT4=1813 F  EXIT5=1753 F  EXIT6=1811 F  EXIT7=1604 F  EXIT8=1630 F  EXIT9=1613 F  EXIT10=1470 F  SP(13')= 2165 F  SP(19')= 2060 F  SP(27')= 1855 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00    J=  0    BASELINE
VALID DATA POINT #   8   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  73

532  14:26:25   79.6   13513    2345   3416  3411  3327  3333    0   16050       2345     218     0       0.17   0.49   1.19         3.4    20.0   14.8   330.0   960.
                                                                                  148      94     0                                    0.0    23.9   17.7   393.7  1145.
 0.0   0.0      85.2             387    623   619   618   614   433               65     159     0                                    3.0    20.5   15.1   337.5   981.
KTRON= 6900  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.60 in H2O  FURNACE P=  0.18 in H2O  COAL P=  3.50 in H2O  MILL OUT=  153 F
T WBOX= 1428 F  SAMPLE= 1288 F  EXIT1=1745 F  EXIT2=1815 F  EXIT3=1747 F  EXIT4=1799 F  EXIT5=1741 F  EXIT6=1802 F  EXIT7=1602 F  EXIT8=1623 F  EXIT9=1624 F  EXIT10=1495 F  SP(13')= 2150 F  SP(19')= 1980 F  SP(27')= 1833 F
SORBENT= LINWOOD    19FT. INJECTION    SORBENT LBS/HR=1051    SORBENT VELOCITY= 159 FT/SEC    SORBENT AIR FLOW=  218  SCFM    [Ca]/[S]=  1.92    J=4642    TEMP INJ(19ft)=  94 F    LINWOOD AT 19FT LEVEL
VALID DATA POINT #   9   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  74

602  15:15:18   78.2   13267    2376   3421  3465  3383  3438    0   16301       2376     218     0       0.18   0.51   1.23         4.0    20.0   14.6   390.0  1350.
                                                                                  145      89     0                                    0.0    24.7   18.0   481.8  1667.
 0.0   0.0      85.2             387    621   618   618   616   392               66     157     0                                    3.0    21.2   15.5   412.9  1429.
KTRON= 6900  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.60 in H2O  FURNACE P=  0.18 in H2O  COAL P=  3.50 in H2O  MILL OUT=  154 F
T WBOX= 1384 F  SAMPLE= 1309 F  EXIT1=1767 F  EXIT2=1837 F  EXIT3=1770 F  EXIT4=1819 F  EXIT5=1752 F  EXIT6=1817 F  EXIT7=1615 F  EXIT8=1635 F  EXIT9=1638 F  EXIT10=1490 F  SP(13')= 2198 F  SP(19')= 2034 F  SP(27')= 1859 F
SORBENT= LINWOOD    19FT. INJECTION    SORBENT LBS/HR= 529    SORBENT VELOCITY= 157 FT/SEC    SORBENT AIR FLOW=  218  SCFM    [Ca]/[S]=  0.98    J=3468    TEMP INJ(19ft)=  89 F    LINWOOD AT 19FT LEVEL
VALID DATA POINT #  10   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  75

618  15:31:00   79.7   13535    2374   3424  3437  3409  3394    0   16256       2374     218     0       0.18   0.49   1.20         3.6    22.0   14.6   400.0  2400.
                                                                                  145       0     0                                    0.0    26.6   17.9   482.8  2696.
 0.0   0.0      85.2             387    618   616   614   613   423               66       0     0                                    3.0    22.8   15.3   413.8  2842.
KTRON= 6900  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.60 in H2O  FURNACE P=  0.18 in H2O  COAL P=  3.50 in H2O  MILL OUT=  152 F
T WBOX= 1572 F  SAMPLE= 1297 F  EXIT1=1748 F  EXIT2=1834 F  EXIT3=1757 F  EXIT4=1806 F  EXIT5=1779 F  EXIT6=1819 F  EXIT7=1592 F  EXIT8=1647 F  EXIT9=1612 F  EXIT10=1478 F  SP(13')= 2194 F  SP(19')= 2042 F  SP(27')= 1848 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00    J=  0    BASELINE
VALID DATA POINT #  11   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  76

657  15:56:55   79.2   13449    2375   2984  3015  2974  2971  1798  16336       2375     218   1798      0.18   0.50   1.21         3.8    25.0   14.6   250.0  2370.
                                                                                  145       0    346                                   0.0    30.5   17.8   305.2  2893.
 0.0   0.0      86.4             388    619   615   616   612   579               66       0     60                                   3.0    26.2   15.3   261.6  2480.
KTRON= 7000  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.60 in H2O  FURNACE P=  0.18 in H2O  COAL P=  3.50 in H2O  MILL OUT=  153 F
T WBOX= 1490 F  SAMPLE= 1262 F  EXIT1=1713 F  EXIT2=1801 F  EXIT3=1701 F  EXIT4=1752 F  EXIT5=1682 F  EXIT6=1747 F  EXIT7=1552 F  EXIT8=1570 F  EXIT9=1540 F  EXIT10=1439 F  SP(13')= 2213 F  SP(19')= 2005 F  SP(27')= 1808 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00    J=  0    BASELINE W/OFA
VALID DATA POINT #  12   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  77
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DATE               :    01-15-86                                    NOZ'L.DES.      :     BASELINE
SYSTEM             :    LWS-INS.                                    SEC.CONFGN      :     ASP
BURNER             :    XCL-80 MKB                                  SPREADER        :     IMPELLER
FUEL               :    OHIO-PITT8                                  OIL CHECK       :     0.24
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            LOAD                 PRIM   V -2   V -3   V -4   V -5   V -6   TOTAL         PRIM      STA    OFA          PRIM  SEC1  SEC2(TOTAL)        O2     CO     CO2     NO     SO2
PT#   TIME  MBTU/HR    TA                             FLOW SCFM                              FLOW SCFM                         SR (CUM)                                 MEASURED
  OIL       CALC       SCFM                                                                    TEMP (F)                                                                CORR TO 0% O2
(%)   LOAD  MEAS                                      TEMP (F)                             VELOCITY (FT/SEC)                                                           CORR TO 3% O2
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664 16:03:1[illegible] 79.7  13521   2362   2964   2978   2980   2932   1804   16239         2362      218    1804         0.17  0.49  1.20               3.6   30.0   14.6   250.0  1590.0
                                                                                           145       89     346                                          0.0   36.2   17.6   301.7  1919.0
0.0   0.0    86.4                389    618    615    615    611    582                    65        157    60                                           3.0   31.0   15.1   258.6  1644.0
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  152 F
T WBOX= 1533 F  SAMPLE= 1277 F  EXIT1=1736 F  EXIT2=1823 F  EXIT3=1725 F  EXIT4=1777 F  EXIT5=1689 F  EXIT6=1758 F  EXIT7=1578 F  EXIT8=1572 F  EXIT9=1599 F  EXIT10=1475 F  SP(13')= 2274 F  SP(19')= 1975 F  SP(27')= 1834 F
SORBENT= LINWOOD     19FT. INJECTION     SORBENT LBS/HR= 523     SORBENT VELOCITY= 157 FT/SEC     SORBENT AIR FLOW=  218  SCFM     [Ca]/[S]=  0.95     J=3455     TEMP INJ(19ft)=  89 F        LINWOOD AT 19FT LEVEL
VALID DATA POINT #  13   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  78

699 16:28:38  82.3  13962        2378   2975   2949   2945   2958   1801   16224         2378      218    1801         0.17  0.48  1.16               3.0   35.0   15.4   220.0  1020.0
                                                                                           144       90     348                                          0.0   40.8   18.0   256.7  1190.0
0.0   0.0    86.4                388    618    614    614    611    580                    66        158    60                                           3.0   35.0   15.4   220.0  1020.0
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  152 F
T WBOX= 1539 F  SAMPLE= 1288 F  EXIT1=1739 F  EXIT2=1827 F  EXIT3=1716 F  EXIT4=1773 F  EXIT5=1690 F  EXIT6=1759 F  EXIT7=1589 F  EXIT8=1577 F  EXIT9=1588 F  EXIT10=1478 F  SP(13')= 2289 F  SP(19')= 1938 F  SP(27')= 1841 F
SORBENT= LINWOOD     19FT. INJECTION     SORBENT LBS/HR=1023     SORBENT VELOCITY= 158 FT/SEC     SORBENT AIR FLOW=  218  SCFM     [Ca]/[S]=  1.81     J=4529     TEMP INJ(19ft)=  90 F        LINWOOD AT 19FT LEVEL
VALID DATA POINT #  14   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  79

717 16:41:21  79.2  13448        2377   2933   2895   2962   2894   1782   16062         2377      218    1782         0.18  0.49  1.19               3.5   50.0   15.0   220.0  2340.0
                                                                                           145       0      353                                          0.0   60.0   18.0   264.0  2808.0
0.0   0.0    86.4                390    620    616    617    612    585                    66        0      60                                           3.0   51.4   15.4   226.3  2406.9
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  150 F
T WBOX= 1389 F  SAMPLE= 1276 F  EXIT1=1732 F  EXIT2=1822 F  EXIT3=1719 F  EXIT4=1772 F  EXIT5=1789 F  EXIT6=1768 F  EXIT7=1572 F  EXIT8=1591 F  EXIT9=1588 F  EXIT10=1472 F  SP(13')= 2281 F  SP(19')= 1980 F  SP(27')= 1829 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0     BASELINE
VALID DATA POINT #  15   ELAPSED TIME, MIN   2   RECORD ON TRK   0   FILE  80

729 16:52:48  79.6  13515        2351   2951   2921   2949   2896   1797   16142         2351      276    1797         0.17  0.49  1.19               3.5   70.0   15.0   220.0   900.0
                                                                                           145       89     351                                          0.0   84.0   18.0   264.0  1080.0
0.0   0.0    86.4                389    620    615    615    612    586                    65        199    60                                           3.0   72.0   15.4   226.3   925.7
KTRON= 7000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.60 in H2O   FURNACE P=  0.18 in H2O   COAL P=  3.50 in H2O   MILL OUT=  152 F
T WBOX= 1552 F  SAMPLE= 1300 F  EXIT1=1741 F  EXIT2=1826 F  EXIT3=1726 F  EXIT4=1782 F  EXIT5=1682 F  EXIT6=1744 F  EXIT7=1595 F  EXIT8=1583 F  EXIT9=1603 F  EXIT10=1493 F  SP(13')= 2279 F  SP(19')= 1965 F  SP(27')= 1837 F
SORBENT= LINWOOD     19FT. INJECTION     SORBENT LBS/HR=1048     SORBENT VELOCITY= 199 FT/SEC     SORBENT AIR FLOW=  276  SCFM     [Ca]/[S]=  1.91     J=6586     TEMP INJ(19ft)=  89 F        LINWOOD AT 19FT LEVEL
VALID DATA POINT #  16   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  81
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DATE                   :    01-16-86                               NOZ'L.DES.    :    BASELINE
SYSTEM                 :    LWS-INS.                               SEC.CONFGN    :    ASP
BURNER                 :    XCL-80  MKB                            SPREADER      :    IMPELLER
FUEL                   :    OHIO-PITT8                             OIL  CHECK    :    -1.68
-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
           LOAD                  PRIM  V -2  V -3  V -4  V -5  V -6  TOTAL           PRIM      S1A    OFA           PRIM   SEC1   SEC2(TOTAL)          O2     CO    CO2     NO     SO2
PT0   TIME MBTU/HR   TA                            FLOW SCFM                             FLOW SCFM                           SR (CUM)                                     MEASURED
 OIL       CALC     SCFM                                                                  TEMP (F)                                                                      CORR TO 0% O2
(%)  LOAD  MEAS                                     TEMP (F)                           VELOCITY (FT/SEC)                                                                CORR TO 3% O2
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 371  11:39:55  75.8   12865     2300  3251  3169  3329  3316    0   15365           2300       0      0            0.18   0.48   1.19                 3.5   20.0   14.8  320.0  2340.0
                                                                                      142       0      0                                                 0.0   24.0   17.8  384.0  2808.0
  0.0   0.0     88.9              376   627   623   622   620   438                    63       0      0                                                 3.0   20.6   15.2  329.1  2406.9
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.50 in H2O   FURNACE P=  0.20 in H2O   COAL P=  3.50 in H2O   MILL OUT=  143 F
T WBOX= 1723 F  SAMPLE= 1238 F  EXIT1=1768 F  EXIT2=1823 F  EXIT3=1751 F  EXIT4=1805 F  EXIT5=1713 F  EXIT6=1791 F  EXIT7=1563 F  EXIT8=1554 F  EXIT9=1552 F  EXIT10=1511 F  SP(13')= 2285 F  SP(19')= 2006 F  SP(27')= 1840 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   1   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  82

 387  11:50:31  78.4   13301     2272  3272  3176  3293  3329    0   15976           2272     635      0            0.17   0.51   1.20                 3.6   18.0   14.9  310.0  1680.0
                                                                                      144      91      0                                                 0.0   21.7   18.0  374.1  2027.6
  0.0   0.0     88.9              383   628   624   625   622   444                    63      41      0                                                 3.0   18.6   15.4  320.7  1737.9
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.30 in H2O   FURNACE P=  0.10 in H2O   COAL P=  3.50 in H2O   MILL OUT=  148 F
T WBOX= 1068 F  SAMPLE= 1247 F  EXIT1=1763 F  EXIT2=1819 F  EXIT3=1736 F  EXIT4=1798 F  EXIT5=1698 F  EXIT6=1783 F  EXIT7=1557 F  EXIT8=1546 F  EXIT9=1546 F  EXIT10=1520 F  SP(13')= 2277 F  SP(19')= 2027 F  SP(27')= 1838 F
SORBENT= VICRON     23FT. INJECTION     SORBENT LBS/HR= 679     SORBENT VELOCITY=  41 FT/SEC     SORBENT AIR FLOW=  635  SCFM     [Ca]/[S]=  1.02     J= 193     TEMP INJ(23ft)=  91 F        VICRON AT 23FT LEVEL
VALID DATA POINT #   2   ELAPSED TIME, MIN   5   RECORD ON TRK   1   FILE  38

 497  13:00:58  78.6   13346     2347  3260  3164  3293  3330    0   16029           2347     635      0            0.18   0.52   1.20                 3.6   10.0   14.8  330.0  2400.0
                                                                                      146       0      0                                                 0.0   12.1   17.9  398.3  2896.6
  0.0   0.0     88.9              386   628   623   623   622   440                    65       0      0                                                 3.0   10.3   15.3  341.4  2482.8
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.30 in H2O   FURNACE P=  0.10 in H2O   COAL P=  3.50 in H2O   MILL OUT=  150 F
T WBOX= 1720 F  SAMPLE= 1260 F  EXIT1=1773 F  EXIT2=1835 F  EXIT3=1750 F  EXIT4=1800 F  EXIT5=1719 F  EXIT6=1784 F  EXIT7=1582 F  EXIT8=1565 F  EXIT9=1555 F  EXIT10=1524 F  SP(13')= 2324 F  SP(19')= 2085 F  SP(27')= 1873 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0
VALID DATA POINT #   3   ELAPSED TIME, MIN   3   RECORD ON TRK   0   FILE  83

 518  13:15:30  78.7   13352     2331  3264  3231  3287  3312    0   16036           2331     612      0            0.17   0.51   1.20                 3.6   20.0   15.2  355.0  1320.0
                                                                                      148      97      0                                                 0.0   24.1   18.3  420.4  1593.1
  0.0   0.0     88.9              388   628   623   623   622   443                    65      40      0                                                 3.0   20.7   15.7  367.2  1365.5
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.30 in H2O   FURNACE P=  0.10 in H2O   COAL P=  3.50 in H2O   MILL OUT=  151 F
T WBOX= 1954 F  SAMPLE= 1208 F  EXIT1=1772 F  EXIT2=1843 F  EXIT3=1737 F  EXIT4=1801 F  EXIT5=1732 F  EXIT6=1816 F  EXIT7=1590 F  EXIT8=1589 F  EXIT9=1559 F  EXIT10=1555 F  SP(13')= 2296 F  SP(19')= 2101 F  SP(27')= 1860 F
SORBENT= VICRON     23FT. INJECTION     SORBENT LBS/HR=1381     SORBENT VELOCITY=  40 FT/SEC     SORBENT AIR FLOW=  612  SCFM     [Ca]/[S]=  2.07     J= 218     TEMP INJ(23ft)=  97 F        VICRON AT 23FT LEVEL
VALID DATA POINT #   4   ELAPSED TIME, MIN   4   RECORD ON TRK   0   FILE  84

 545  13:35:57  79.5   13496     2325  3269  3192  3337  3362    0   16029           2325     544      0            0.17   0.51   1.19                 3.4   40.0   15.2  370.0  1140.0
                                                                                      149     104      0                                                 0.0   47.7   18.1  441.5  1360.2
  0.0   0.0     88.9              391   625   621   622   618   431                    65      36      0                                                 3.0   40.9   15.5  378.4  1165.9
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.30 in H2O   FURNACE P=  0.10 in H2O   COAL P=  3.50 in H2O   MILL OUT=  154 F
T WBOX= 1595 F  SAMPLE= 1315 F  EXIT1=1778 F  EXIT2=1852 F  EXIT3=1761 F  EXIT4=1822 F  EXIT5=1741 F  EXIT6=1822 F  EXIT7=1620 F  EXIT8=1618 F  EXIT9=1604 F  EXIT10=1550 F  SP(13')= 2343 F  SP(19')= 2112 F  SP(27')= 1860 F
SORBENT= VICRON     23FT. INJECTION     SORBENT LBS/HR=2057     SORBENT VELOCITY=  36 FT/SEC     SORBENT AIR FLOW=  544  SCFM     [Ca]/[S]=  3.06     J= 212     TEMP INJ(23ft)= 104 F        VICRON AT 23FT LEVEL
VALID DATA POINT #   5   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  85

 567  13:51:41  79.0   13412     2296  3270  3281  3279  3375    0   16019           2296     598      0            0.17   0.51   1.19                 3.5   18.0   15.2  330.0  2720.0
                                                                                      149       0      0                                                 0.0   21.6   18.2  396.0  2664.0
  0.0   0.0     88.9              390   627   622   621   619   436                    64       0      0                                                 3.0   18.5   15.6  339.4  2243.4
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.30 in H2O   FURNACE P=  0.10 in H2O   COAL P=  3.50 in H2O   MILL OUT=  155 F
T WBOX= 1660 F  SAMPLE= 1305 F  EXIT1=1780 F  EXIT2=1851 F  EXIT3=1752 F  EXIT4=1811 F  EXIT5=1750 F  EXIT6=1823 F  EXIT7=1616 F  EXIT8=1624 F  EXIT9=1601 F  EXIT10=1540 F  SP(13')= 2312 F  SP(19')= 2155 F  SP(27')= 1875 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     [Ca]/[S]=  0.00     J=   0    BASELINE
VALID DATA POINT #   6   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  86
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DATE      :  01-16-86                              NOZ'L.DES.   :  BASELINE
SYSTEM    :  LWS-INS.                              SEC.CONFGN   :  ASP
BURNER    :  XCL-80 MKB                            SPREADER     :  IMPELLER
FUEL      :  OHIO-PITT8                            OIL  CHECK   :  -1.60
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            LOAD            PRIM  V -2  V -3  V -4  V -5  V -6  TOTAL        PRIM    STA    OFA         PRIM  SEC1  SEC2(TOTAL)     O2   CO    CO2    NO    SO2
PT#   TIME  MBTU/HR   TA                    FLOW SCFM                        FLOW SCFM                   SR (CUM)                             MEASURED
  OIL       CALC     SCFM                                                    TEMP (F)                                                     CORR TO 0% O2
(%)   LOAD  MEAS                            TEMP (F)                         VELOCITY (FT/SEC)                                            CORR TO 3% O2
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 581  14:03:00  79.3  13457   2290  3337  3220  3295  3415     0  16163       2290    590     0         0.17  0.51  1.20            3.6  10.0  15.0  300.0  750.0
                                                                              149     98     0                                      0.0  12.1  18.1  362.1  905.2
 0.0  0.0       80.9           386   626   621   621   619   438              64     39     0                                      3.0  10.3  15.5  310.3  775.9
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.30 in H2O  FURNACE P=  0.10 in H2O  COAL P=  3.50 in H2O  MILL OUT=  153 F
T WBOX= 1631 F  SAMPLE= 1329 F  EXIT1=1801 F  EXIT2=1876 F  EXIT3=1770 F  EXIT4=1839 F  EXIT5=1739 F  EXIT6=1826 F  EXIT7=1644 F  EXIT8=1627 F  EXIT9=1629 F  EXIT10=1611 F  SP(13')= 2303 F  SP(19')= 2205 F  SP(27')= 1898 F
SORBENT= VICRON    23FT. INJECTION    SORBENT LBS/HR= 968    SORBENT VELOCITY=  39 FT/SEC    SORBENT AIR FLOW=  590  SCFM    [Ca]/[S]=  1.44    J= 190    TEMP INJ(23ft)=  98 F       LINWOOD AT 23FT LEVEL
VALID DATA POINT #  7  ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  88

 649  14:47:52  80.3  13627   2285  3355  3304  3345  3358     0  16276       2285    620     0         0.17  0.51  1.19            3.5  35.0  15.4  340.0  2190.0
                                                                              149      0     0                                      0.0  42.0  18.5  408.0  2628.0
 0.0  0.0       80.9           403   624   619   619   618   438              64      0     0                                      3.0  36.0  15.0  349.7  2252.6
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.30 in H2O  FURNACE P=  0.10 in H2O  COAL P=  3.50 in H2O  MILL OUT=  156 F
T WBOX= 1639 F  SAMPLE= 1316 F  EXIT1=1782 F  EXIT2=1864 F  EXIT3=1757 F  EXIT4=1813 F  EXIT5=1746 F  EXIT6=1818 F  EXIT7=1624 F  EXIT8=1625 F  EXIT9=1605 F  EXIT10=1567 F  SP(13')= 2305 F  SP(19')= 2264 F  SP(27')= 1891 F
SORBENT LBS/HR=   0    SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00    J=   0    BASELINE
VALID DATA POINT #  8  ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  89

 664  14:57:30  80.1  13590   2313  3324  3221  3369  3377     0  16232       2313    620     0         0.17  0.51  1.19            3.5  40.0  15.2  350.0  1440.0
                                                                              149     92     0                                      0.0  48.0  18.2  420.0  1728.0
 0.0  0.0       80.9           398   624   620   620   618   428              64     41     0                                      3.0  41.1  15.6  360.0  1481.1
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.30 in H2O  FURNACE P=  0.10 in H2O  COAL P=  3.50 in H2O  MILL OUT=  156 F
T WBOX= 1609 F  SAMPLE= 1324 F  EXIT1=1792 F  EXIT2=1869 F  EXIT3=1764 F  EXIT4=1816 F  EXIT5=1752 F  EXIT6=1815 F  EXIT7=1629 F  EXIT8=1625 F  EXIT9=1624 F  EXIT10=1568 F  SP(13')= 2299 F  SP(19')= 2261 F  SP(27')= 1898 F
SORBENT= COLTON    23FT. INJECTION    SORBENT LBS/HR= 510    SORBENT VELOCITY=  41 FT/SEC    SORBENT AIR FLOW=  620  SCFM    [Ca]/[S]=  1.00    J= 182    TEMP INJ(23ft)=  92 F       COLTON AT 23FT LEVEL
VALID DATA POINT #  9  ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  91

 677  15:11:54  80.7  13700   2249  3343  3261  3408  3401     0  16272       2249    610     0         0.16  0.50  1.19            3.4  20.0  15.4  290.0  2220.0
                                                                              150      0     0                                      0.0  23.9  18.4  346.0  2648.9
 0.0  0.0       80.9           402   623   620   620   616   397              63      0     0                                      3.0  20.5  15.8  296.6  2270.5
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.30 in H2O  FURNACE P=  0.10 in H2O  COAL P=  3.50 in H2O  MILL OUT=  157 F
T WBOX= 1760 F  SAMPLE= 1324 F  EXIT1=1781 F  EXIT2=1854 F  EXIT3=1752 F  EXIT4=1805 F  EXIT5=1742 F  EXIT6=1809 F  EXIT7=1623 F  EXIT8=1626 F  EXIT9=1617 F  EXIT10=1542 F  SP(13')= 2330 F  SP(19')= 2260 F  SP(27')= 1880 F
SORBENT LBS/HR=   0    SORBENT VELOCITY=   0 FT/SEC    SORBENT AIR FLOW=    0  SCFM    [Ca]/[S]=  0.00    J=   0    BASELINE
VALID DATA POINT #  10  ELAPSED TIME, MIN   5   RECORD ON TRK   1   FILE  99

 695  15:20:55  82.0  13915   2317  3331  3287  3350  3436     0  16346       2317    624     0         0.17  0.50  1.17            3.2  20.0  15.4  350.0  1260.0
                                                                              148     92     0                                      0.0  23.6  18.2  412.9  1486.5
 0.0  0.0       80.9           400   622   619   619   616   420              64     40     0                                      3.0  20.2  15.6  353.9  1274.2
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.30 in H2O  FURNACE P=  0.10 in H2O  COAL P=  3.50 in H2O  MILL OUT=  157 F
T WBOX= 1713 F  SAMPLE= 1352 F  EXIT1=1800 F  EXIT2=1875 F  EXIT3=1770 F  EXIT4=1821 F  EXIT5=1767 F  EXIT6=1826 F  EXIT7=1646 F  EXIT8=1647 F  EXIT9=1641 F  EXIT10=1583 F  SP(13')= 2314 F  SP(19')= 2270 F  SP(27')= 1902 F
SORBENT= COLTON    23FT. INJECTION    SORBENT LBS/HR=1030    SORBENT VELOCITY=  40 FT/SEC    SORBENT AIR FLOW=  624  SCFM    [Ca]/[S]=  1.94    J= 205    TEMP INJ(23ft)=  92 F       COLTON AT 23FT LEVEL
VALID DATA POINT #  11  ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  92

 727  15:52:09  82.6  14025   2344  3305  3300  3378  3395     0  16297       2344    576     0         0.17  0.49  1.16            3.0  35.0  15.4  350.0  1080.0
                                                                              148     96     0                                      0.0  40.0  18.0  408.3  1260.0
 0.0  0.0       80.9           396   622   619   620   616   410              65     38     0                                      3.0  35.0  15.4  350.0  1080.0
KTRON= 7200  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  0.0  in  OUT REG=  50 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.30 in H2O  FURNACE P=  0.10 in H2O  COAL P=  3.50 in H2O  MILL OUT=  155 F
T WBOX= 1707 F  SAMPLE= 1372 F  EXIT1=1804 F  EXIT2=1896 F  EXIT3=1801 F  EXIT4=1859 F  EXIT5=1814 F  EXIT6=1869 F  EXIT7=1657 F  EXIT8=1687 F  EXIT9=1667 F  EXIT10=1585 F  SP(13')= 2342 F  SP(19')= 2268 F  SP(27')= 1902 F
SORBENT= COLTON    23FT. INJECTION    SORBENT LBS/HR=1406    SORBENT VELOCITY=  38 FT/SEC    SORBENT AIR FLOW=  576  SCFM    [Ca]/[S]=  2.62    J= 198    TEMP INJ(23ft)=  96 F       COLTON AT 23FT LEVEL
VALID DATA POINT #12  ELAPSED TIME, MIN  5  RECORD ON TRK  0  FILE 93
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DATE        :   01-16-86                      NOZ'L.DES.   :   BASELINE
SYSTEM      :   LWS-INS.                      SEC.CONFGN   :   ASP
BURNER      :   XCL-80  MKB                   SPREADER     :   IMPELLER
FUEL        :   OHIO-PITT8                    OIL  CHECK   :   -1.60
--------------------------------------------------------------------------------------------------------------------------------------------
            LOAD                PRIM   V-2    V-3    V-4    V-5    V-6   TOTAL        PRIM     STA    OFA        PRIM   SEC1   SEC2(TOTAL)        O2    CO    CO2    NO     SO2
PT0  TIME   MBTU/HR   TA                             FLOW SCFM                           FLOW SCFM                          SR (CUM)                                  MEASURED
 OIL        CALC      SCFM                                                                TEMP (F)                                                                   CORR TO 0% O2
(%)  LOAD   MEAS                                     TEMP (F)                       VELOCITY (FT/SEC)                                                                CORR TO 3% O2
--------------------------------------------------------------------------------------------------------------------------------------------
737  15:59:52  80.6  13689      2320   3350   3265   3336   3412     0   16250       2320     576      0         0.17   0.50   1.19
                                                                                   147       0      0                                               3.4   45.0   14.0   330.0  2220.
 0.0  0.0      80.9             398    621    618    619    614    407                64       0      0                                               0.0   53.7   16.7   393.7  2640.
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =  0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.30 in H20   FURNACE P=  0.10 in H20   COAL P=  3.50 in H20   MILL OUT=  154 F      3.0   46.0   14.3   337.5  2270.
T WBOX= 1723 F  SAMPLE= 1361 F  EXIT1=1824 F  EXIT2=1887 F  EXIT3=1801 F  EXIT4=1840 F  EXITS=1759 F  EXIT6=1823 F  EXIT7=1672 F  EXIT8=1653 F  EXIT9=1655 F  EXIT10=1577 F  SP(13')= 2339 F  SP(19')= 2267 F  SP(27')= 1919 F
SORBENT LBS/HR=  0     SORBENT VELOCITY=  0 FT/SEC     SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0    BASELINE
VALID DATA POINT #  13   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  94

751  16:10:57  78.0  13300      2323   3300   3235   3344   3353     0   16870       2323     500      0         0.17   0.51   1.20
                                                                                   146     100      0                                               3.6   60.0   15.0   380.0  1140.
 0.0  0.0      80.9             397    621    618    610    613    398                64      33      0                                               0.0   72.4   18.1   450.6  1375.
KTRON= 7200   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =  0.0  in   OUT REG=  50 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  3.30 in H20   FURNACE P=  0.10 in H20   COAL P=  3.50 in H20   MILL OUT=  152 F      3.0   62.1   15.5   393.1  1179..
T WBOX= 1754 F  SAMPLE= 1366 F  EXIT1=1805 F  EXIT2=1878 F  EXIT3=1779 F  EXIT4=1835 F  EXITS=1767 F  EXIT6=1832 F  EXIT7=1653 F  EXIT8=1657 F  EXIT9=1656 F  EXIT10=1577 F  SP(13')= 2329 F  SP(19')= 2257 F  SP(27')= 1906 F
SORBENT= COLTON     23FT. INJECTION     SORBENT LBS/HR=1013     SORBENT VELOCITY=  33 FT/SEC     SORBENT AIR FLOW=  500  SCFM     [Ca]/[S]=  1.98     J= 146    TEMP INJ(23ft)= 100 F        COLTON AT 23FT LEVEL
VALID DATA POINT #  14   ELAPSED TIME, MIN   5   RECORD ON TRK   0   FILE  95
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DATE                 :   01-17-86                                   NOZ'L.DES.      :   BASELINE
SYSTEM               :   LWS-INS.                                   SEC.CONFGN      :   ASP
BURNER               :   XCL-80  MKB                                SPREADER        :   IMPELLER
FUEL                 :   DANISH                                     OIL  CHECK      :   0.48
--------------------------------------------------------------------------------------------------------------------------------------------
            LOAD               PRIM  V -2  V -3  V -4  V -5  V -6  TOTAL       PRIM     STA    DFA          PRIM   SEC1  SEC2(TOTAL)     O2    CO    CO2    NO    S
PT0  TIME  MBTU/HR    TA                         FLOW SCFM                       FLOW SCFM                          SR (CUM)                         MEASURED
 OIL        CALC     SCFM                                                        TEMP (F)                                                           CORR TO 0% O2
(%)  LOAD   MEAS                                 TEMP (F)                    VELOCITY (FT/SEC)                                                      CORR TO 3% O2
--------------------------------------------------------------------------------------------------------------------------------------------

 115  09:24:25  92.3  15708     2306  3511  3366  3518  3608  3468  19778      2306      0      0          0.15   0.48   1.26           4.4   40.0   14.2  510.0   0.
                                                                                 125      0      0                                         0.0   50.6   18.0  645.2   0
 50.0 21.7      84.1             391   595   593   593   590   580                62      0      0                                         3.0   43.4   15.4  553.0   0.
KTRON= 7000  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  2.0  in  OUT REG= 40 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  5.00 in H2O  FURNACE P=  0.30 in H2O  COAL P=  4.00 in H2O  MILL OUT=  121 F
T WBOX= 1532 F  SAMPLE= 1345 F  EXIT1=1761 F  EXIT2=1833 F  EXIT3=1799 F  EXIT4=1833 F  EXIT5=1817 F  EXIT6=1837 F  EXIT7=1601 F  EXIT8=1677 F  EXIT9=1638 F  EXIT10=1519 F  SP(13')= 2294 F  SP(19')= 2093 F  SP(27')= 1780 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0    OIL AND COAL BASELINE -  FULL LOAD
VALID DATA POINT #  1   ELAPSED TIME, MIN   5   RECORD ON TRK   1   FILE   1

 199  10:26:05  75.2  12812     2317  3338  3299  3424  3472     0  15849      2317      0      0          0.18   0.50   1.24           4.1    8.0   14.8  465.0   0.
                                                                                 133      0      0                                         0.0    9.9   18.4  577.8   0.
  0.0  0.0      90.1             450   593   591   592   591   492                63      0      0                                         3.0    8.5   15.8  495.3   0.
KTRON= 7500  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  2.0  in  OUT REG= 40 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  4.40 in H2O  FURNACE P=  0.18 in H2O  COAL P=  2.70 in H2O  MILL OUT=  133 F
T WBOX= 1637 F  SAMPLE= 1269 F  EXIT1=1734 F  EXIT2=1807 F  EXIT3=1749 F  EXIT4=1783 F  EXIT5=1697 F  EXIT6=1769 F  EXIT7=1612 F  EXIT8=1564 F  EXIT9=1608 F  EXIT10=   0 F  SP(13')=    0 F  SP(19')= 2051 F  SP(27')= 1757 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0    COAL ONLY BASELINE - FULL LOAD
VALID DATA POINT #  2   ELAPSED TIME, MIN   5   RECORD ON TRK   1   FILE   2

 281  11:18:43  76.1  12964     2269  4054  4054  4112  4156     0  18644      2269      0      0          0.18   0.55   1.44           6.5   15.0   15.0  460.0   0
                                                                                 136      0      0                                         0.0   21.7   21.7  666.2   0.
  0.0  0.0      90.1             469   605   603   602   601   512                62      0      0                                         3.0   18.6   18.6  571.0   0.
KTRON= 7500  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  2.0  in  OUT REG= 40 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  4.40 in H2O  FURNACE P=  0.18 in H2O  COAL P=  2.70 in H2O  MILL OUT=  136 F
T WBOX= 1978 F  SAMPLE= 1327 F  EXIT1=1765 F  EXIT2=1656 F  EXIT3=1781 F  EXIT4=1828 F  EXIT5=1700 F  EXIT6=1769 F  EXIT7=1625 F  EXIT8=1588 F  EXIT9=1627 F  EXIT10=   0 F  SP(13')= 2494 F  SP(19')= 2021 F  SP(27')= 1731 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0    EXCESS AIR - 6.5% O2
VALID DATA POINT #  3   ELAPSED TIME, MIN   5   RECORD ON TRK   1   FILE   3

 304  11:33:01  80.2  13657     2359  4842  4944  4921  4973     0  22038      2359      0      0          0.17   0.61   1.61           8.1   25.0   11.3  390.0   0.
                                                                                 134      0      0                                         0.0   40.7   18.4  634.9   0.
  0.0  0.0      90.1             430   589   587   586   586   508                64      0      0                                         3.0   34.9   15.8  544.2   0.
KTRON= 7500  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER =  2.0  in  OUT REG= 40 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  4.40 in H2O  FURNACE P=  0.18 in H2O  COAL P=  2.70 in H2O  MILL OUT=  133 F
T WBOX= 1780 F  SAMPLE= 1349 F  EXIT1=1728 F  EXIT2=1795 F  EXIT3=1734 F  EXIT4=1771 F  EXIT5=1673 F  EXIT6=1731 F  EXIT7=1604 F  EXIT8=1568 F  EXIT9=1606 F  EXIT10=   0 F  SP(13')= 2488 F  SP(19')= 1955 F  SP(27')= 1713 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0    EXCESS AIR - 8.1% O2
VALID DATA POINT #  4   ELAPSED TIME, MIN   6   RECORD ON TRK   1   FILE   4

 403  12:41:47  79.7  13565     2268  4637  4749  4698  4732     0  21084      2268      0      0          0.17   0.58   1.55           7.6   25.0   12.2  355.0   0
                                                                                 138      0      0                                         0.0   39.2   19.1  556.3   0.
  0.0  0.0      90.1             462   582   580   579   581   493                62      0      0                                         3.0   33.6   16.4  476.9   0.
KTRON= 7500  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER = -6.0  in  OUT REG= 60 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  4.40 in H2O  FURNACE P=  0.18 in H2O  COAL P=  2.70 in H2O  MILL OUT=  137 F
T WBOX= 2053 F  SAMPLE= 1357 F  EXIT1=1719 F  EXIT2=1795 F  EXIT3=1725 F  EXIT4=1793 F  EXIT5=1737 F  EXIT6=1777 F  EXIT7=1600 F  EXIT8=1580 F  EXIT9=1582 F  EXIT10=   0 F  SP(13')= 2450 F  SP(19')= 1926 F  SP(27')= 1698 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0    EXCESS AIR - 7.1% O2 - LONG FLAME
VALID DATA POINT #  5   ELAPSED TIME, MIN   5   RECORD ON TRK   1   FILE   5

 422  12:54:53  78.4  13356     2192  3416  3298  3491  3570     0  15967      2192      0      0          0.16   0.47   1.20           3.5   40.0    0.0  270.0   0.
                                                                                 140      0      0                                         0.0   48.0    0.0  324.0   0.
  0.0  0.0      90.1             485   595   592   593   592   484                60      0      0                                         3.0   41.1    0.0  277.7   0
KTRON= 7500  SLEEVE #1 =  3.00 in  SLEEVE #2 = -6.50 in  SPREADER = -6.0  in  OUT REG= 40 (CW)DEG  IN REG =  30 (CW)DEG  P WBOX=  3.30 in H2O  FURNACE P=  0.12 in H2O  COAL P=  5.00 in H2O  MILL OUT=  140 F
T WBOX= 2015 F  SAMPLE= 1343 F  EXIT1=1802 F  EXIT2=2286 F  EXIT3=1837 F  EXIT4=1902 F  EXIT5=1837 F  EXIT6=1896 F  EXIT7=1673 F  EXIT8=1665 F  EXIT9=1667 F  EXIT10=   0 F  SP(13')= 2277 F  SP(19')= 2022 F  SP(27')= 1745 F
SORBENT LBS/HR=  0    SORBENT VELOCITY=  0 FT/SEC    SORBENT AIR FLOW=   0  SCFM    [Ca]/[S]=  0.00    J=  0    BASELINE - FULL LOAD - LONG FLAME
 VALID DATA POINT #  6 ELAPSED TIME, MIN  5  RECORD ON TRK  1  FILE  6
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DATE          :   01-17-86               NOZ'L.DES.   :   BASELINE
SYSTEM        :   LWS-INS.               SEC.CONFGN   :   ASP
BURNER        :   XCL-80  MKB            SPREADER     :   IMPELLER
FUEL          :   DANISH                 OIL  CHECK   :   0.48
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               LOAD           PRIN   V -2   V -3   V -4   V -5   V -6   TOTAL       PRIN      STA     OFA        PRIN   SEC1   SEC2(TOTAL)     O2     CO     CO2     NO     SO2
PT0    TIME   KBTU/HR   TA                        FLOW SCFM                              FLOW SCFM                        SR (CUM)                        MEASURED
  OIL           CALC    SCFM                                                             TEMP (F)                                                         CORR TO 0% O2
(%)    LOAD     MEAS                              TEMP (F)                             VELOCITY (FT/SEC)                                                  CORR TO 3% O2
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543  14:09:17  65.3   11119   2325   3600   3523   3616   3606     0   16669        2325      0       0         0.21   0.60   1.50            7.1   25.0   12.2   290.0   0.0
                                                                                   144      0       0                                         0.0   37.8   18.4   438.1   0.
 0.0   0.0     72.1            467    595    593    593    592    510                64      0       0                                         3.0   32.4   15.8   375.5   0.
KTRON= 6000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   2.0  in   OUT REG= 40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  4.50 in H20   FURNACE P=  0.24 in H20   COAL P=  3.00 in H20   MILL OUT=  149 F
T WBOX= 1076 F  SAMPLE= 1271 F  EXIT1=1696 F  EXIT2=2361 F  EXIT3=1707 F  EXIT4=1754 F  EXIT5=1653 F  EXIT6=1727 F  EXIT7=1569 F  EXIT8=1549 F  EXIT9=1555 F  EXIT10=   0 F  SP(13')=    0 F  SP(19')= 1943 F  SP(27')= 1671 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     (Ca)/(S)=  0.00     J=   0    EXCESS AIR - 7.1%02 - PART LOAD
VALID DATA POINT #   7   ELAPSED TIME, MIN   5   RECORD ON TRK   1   FILE   7

570  14:34:04  61.9   10541   2297   2667   2429   2689   2736     0   12817        2297      0       0         0.22   0.52   1.22            3.8   15.0   15.2   220.0   0.
                                                                                   142      0       0                                         0.0   18.3   18.6   260.6   0.
 0.0   0.0     72.1            464    604    601    603    600    463                63      0       0                                         3.0   15.7   15.9   230.2   0.
KTRON= 6000   SLEEVE #1 =  3.00 in   SLEEVE #2 = -6.50 in   SPREADER =   2.0  in   OUT REG=  40 (CW)DEG   IN REG =  30 (CW)DEG   P WBOX=  2.60 in H20   FURNACE P=  0.12 in H20   COAL P=  3.00 in H20   MILL OUT=  148 F
T WBOX= 1999 F  SAMPLE= 1226 F  EXIT1=1744 F  EXIT2=2204 F  EXIT3=1774 F  EXIT4=1807 F  EXIT5=1676 F  EXIT6=1762 F  EXIT7=1604 F  EXIT8=1558 F  EXIT9=1600 F  EXIT10=   0 F  SP(13')= 2331 F  SP(19')= 1929 F  SP(27')= 1670 F
SORBENT LBS/HR=   0     SORBENT VELOCITY=   0 FT/SEC     SORBENT AIR FLOW=    0  SCFM     (Ca)/(S)=  0.00     J=   0    BASELINE - 60MKB
VALID DATA POINT #   8   ELAPSED TIME, MIN   5   RECORD ON TRK   1   FILE   8
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